EVALUATION OF AN EXPERIMENTAL RECYCLED-WATER SYSTEM FOR BRACKISH WATER AQUACULTURE

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ABSTRACT

New Mexico has a vast reserve of brackish water that is unsuitable for production of traditional agricultural crops. Preliminary studies have indicated that this water could be utilized for aquaculture. Evaporation and erratic water temperatures, however, have been deterrants to aquaculture in this state. A possible solution to these problems is the use of indoor, recycled-water systems. A system was tested to determine the effectiveness of various filtration techniques for recycling effluent water.

Recycled-water systems data suggest that several aspects of these systems have potential for high yield aquaculture. Tilapia, _Tilapia nilotica_, increased their total biomass 870 percent in 56 days while being fed only catfish feces and uneaten fish food flushed from vertical raceway sumps. A biofilter, composed of volcanic ash rock and chemoautotrophic bacteria, was shown to be effective for removal of ammonia through nitrification.

The data also suggest that even though these systems are potentially feasible, there is a need for further development, adaptation, and testing of component parts.

Keywords: brackish water*, aquaculture*, recycling water, biofilter, tilapia, catfish, vertical raceways*.

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INTRODUCTION

Commercial production of channel catfish, Ictalurus punctatus (Rafinesque), especially in the southeastern United States, has expanded rapidly over the last several years. For example, production increased at an average rate of 25 percent per year from 1975 to 1981 and reached a peak of 62,000 tons in 1982 (U.S.D.A. 1981; Anonymous 1984). Even so, demand far exceeds supply, thereby creating the potential for new enterprise in this multimillion dollar industry. This potential is especially true in states like New Mexico where resources for production exist but where there currently is little or no commercial aquaculture venture.

Total New Mexico groundwater reserves, which includes both fresh and brackish water, has been estimated to be 20 billion acre-feet, 75 percent of which exceeds salinities of 3000 mg/l TDS (Bahr and Herman 1981). Hence, the commercial production of channel catfish, or any other plant or animal species which could be cultured in brackish water, could result in economic benefit derived from a resource that is unsuited for producing more conventional agricultural crops.

In the early 1970s, the Soil Conservation Service (SCS), U.S. Department of Agriculture (USDA), conducted field trials to determine if channel catfish could be produced commercially in the Pecos River Valley of southeastern New Mexico. Results of these trials indicated that commercial production was feasible but showed a need to solve problems caused by limited and fluctuating water sources, erratic water temperatures, and evaporation (Slone et al. 1981).

In 1983 the New Mexico State Legislature appropriated $200,000 to be administered through the New Mexico Water Resources Research Institute (WRRI), for research in saline water aquaculture in the Pecos River Valley. Results from a portion of this research have provided more specific information about culturing channel catfish in saline water that contains high concentrations of sulfate ions (10 percent of salt concentration). Catfish can be grown optimally in groundwaters with salinities as high as 5,000 mg/l TDS. Growth is suppressed at 7,000 mg/l TDS, but fish grow sufficiently well to allow for culture at that level, provided more time is allowed for them to reach marketable size. At 9,000 mg/l TDS, it becomes impractical to culture channel catfish because of poor growth, inefficient food conversion and increased mortality (Turnbull 1984).

The existance of suitable quantities of culture water has been established. Now the problem becomes one of economics. The cultured species must be grown to an acceptable size in such a way that the commercial producer is able to make a profit from the venture. The problems of erratic water temperatures and evaporation might be overcome by the use of intensive, indoor recirculating water systems.

Recirculating systems have the potential for maximum conservation and utilization of water, heat conservation, high production rates, disease control, minimum discharge of effluents, and freedom from normal site limitations (Muir 1981; Slone et al. 1981). Additionally, harvest dates could be selected to take advantage of high seasonal market prices for some cultured species. However, these systems are not without problems. Proper management requires control of dissolved oxygen (DO), nitrogenous wastes, hydrogen-ion concentration (pH), and settleable organic solids that generate biochemical oxygen demand (BOD) and toxic gases (Slone et al. 1981).

The objective of this study was to test a laboratory-scale high-density-and-biomass channel catfish culture system integrating various filtration techniques which would deal effectively with the problems listed above.

METHODS AND MATERIALS

All components of the system described in this report were constructed from plastic, fiberglass, polyvinyl chloride (PVC), copolyvinyl chloride (CPVC), glass, silicone, rubber, or materials coated with epoxy paint to prevent contamination of culture water by metallic ions and to prevent corrosion of the system.

The test system contained 15 vertical raceways, a foam fractionation-aeration (FFA) unit, a clinoptilolite filter, a biofilter, and a tilapia tank (figures 1 and 2). The system contained 152 gal. of water.

The vertical raceways, each capable of holding 0.5 ft.^{3} of water, were inverted 5 gal. plastic jugs from which the bottoms had been removed (figure 3). A piece of 0.3 in. mesh plastic screen separated the neck portion from the remainder of the container and a rubber stopper with a 0.5 in. hole in the center was inserted into the neck. The neck portion of the container functioned as a settleable solids sump which collected feces and uneaten feed. A length of 0.5 in. plastic tubing inserted into the stopper hole functioned as a sump drain line that carried the solid waste to a settleable solids manifold, which in turn emptied into the tilapia tank. The function of the tilapia tank will be discussed below. Rate of flow through the sump drain lines was regulated by screw clamps. It was intended that sumps would flush continuously; however, frequent clogging required complete opening of screw clamps twice daily.

Each raceway contained a FFA component constructed of 1.5 in. PVC pipe (figure 4). Foam from these components was collected in an overhead collection chamber and carried by gravity flow, to the tilapia tank. Raceways were covered with a 0.3 in. mesh plastic screen to prevent fish from jumping out. Effluent water overflowed from the raceways through a 0.5 in. hole located 1 in. from the top. Water drained into a 1 in. vertical pipe and from there into a 1.5 in. horizontal raceway effluent manifold which carried water, by gravity flow, to the FFA unit.

Foam fractionation, also called air stripping or protein skimming, functions as a mechanical filtration device for removal of dissolved organic carbon (DOC) and particulate organic carbon (POC). This filtration is accomplished with DOC by using rising air bubbles in a

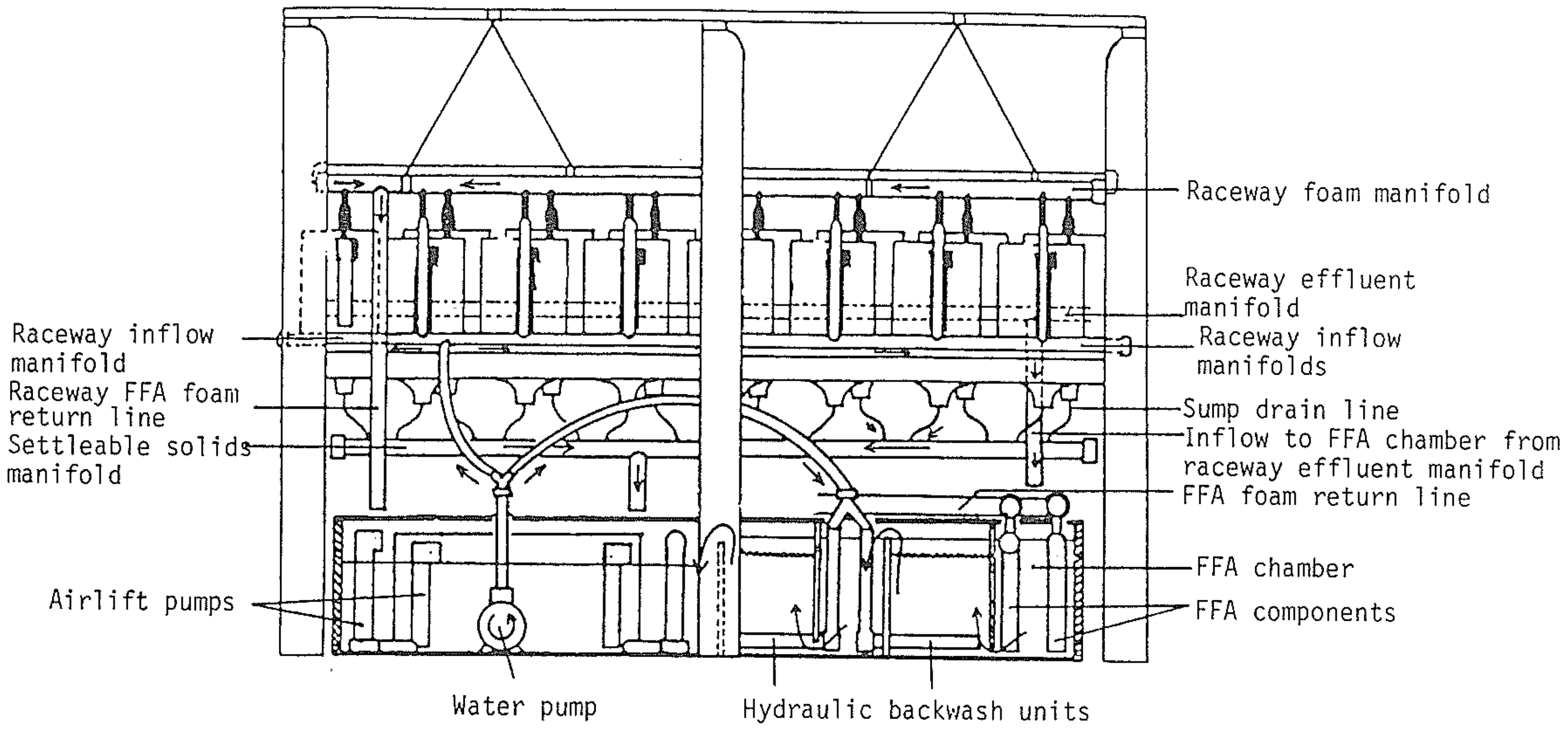

Figure 1. Sideview of test system.

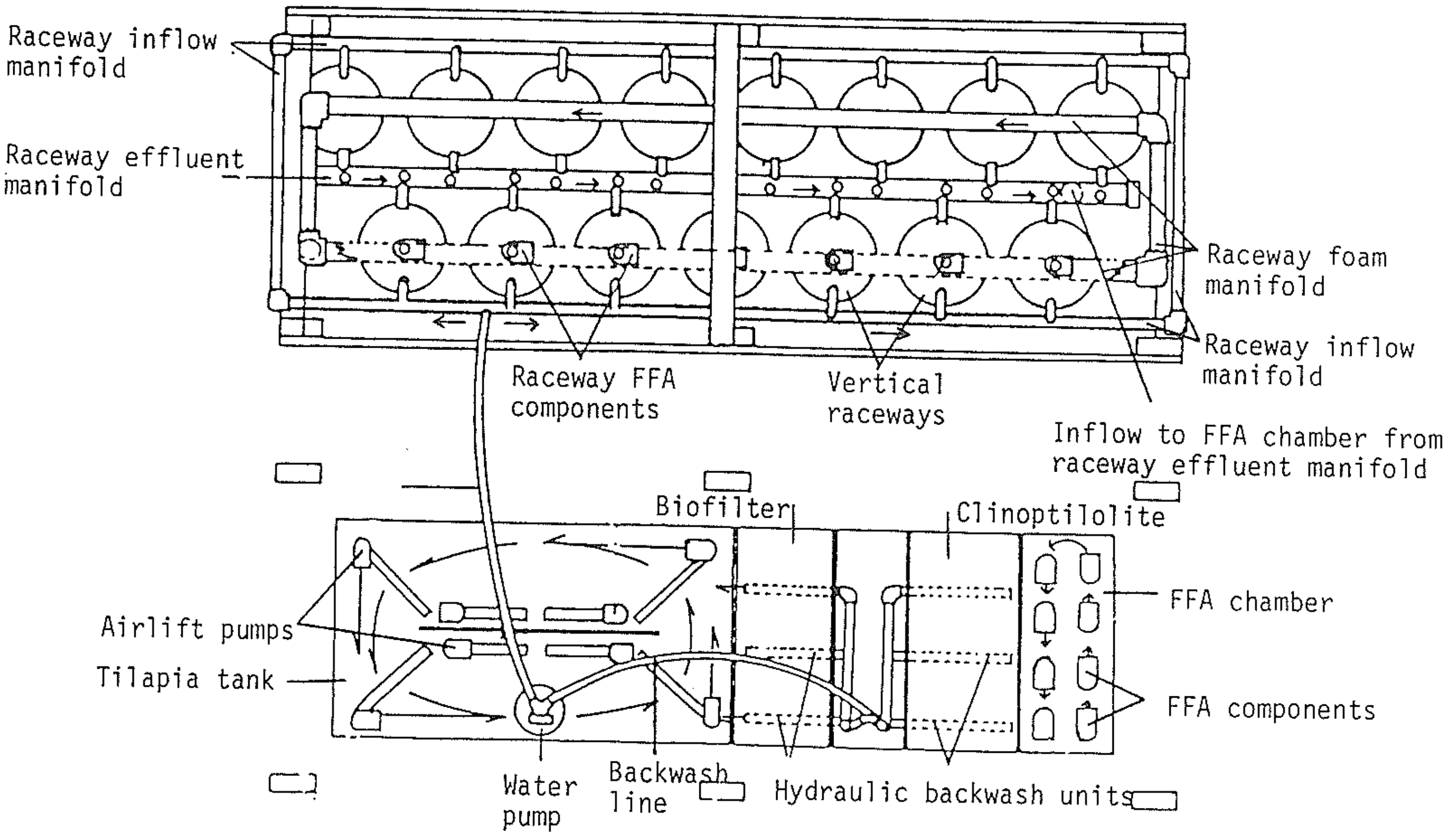

Figure 2. Overview of test system.

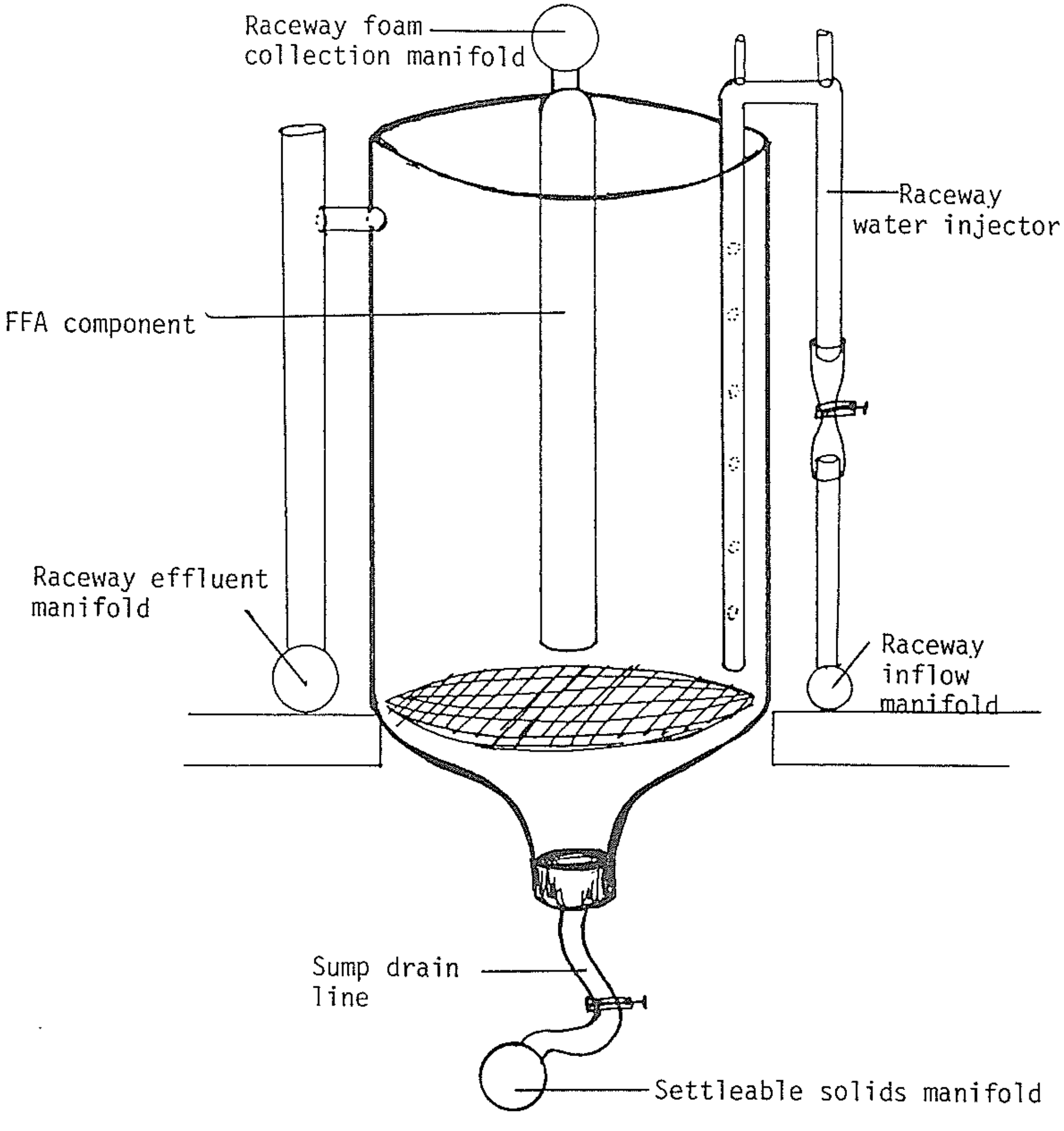

Figure 3. Vertical raceway and component parts.

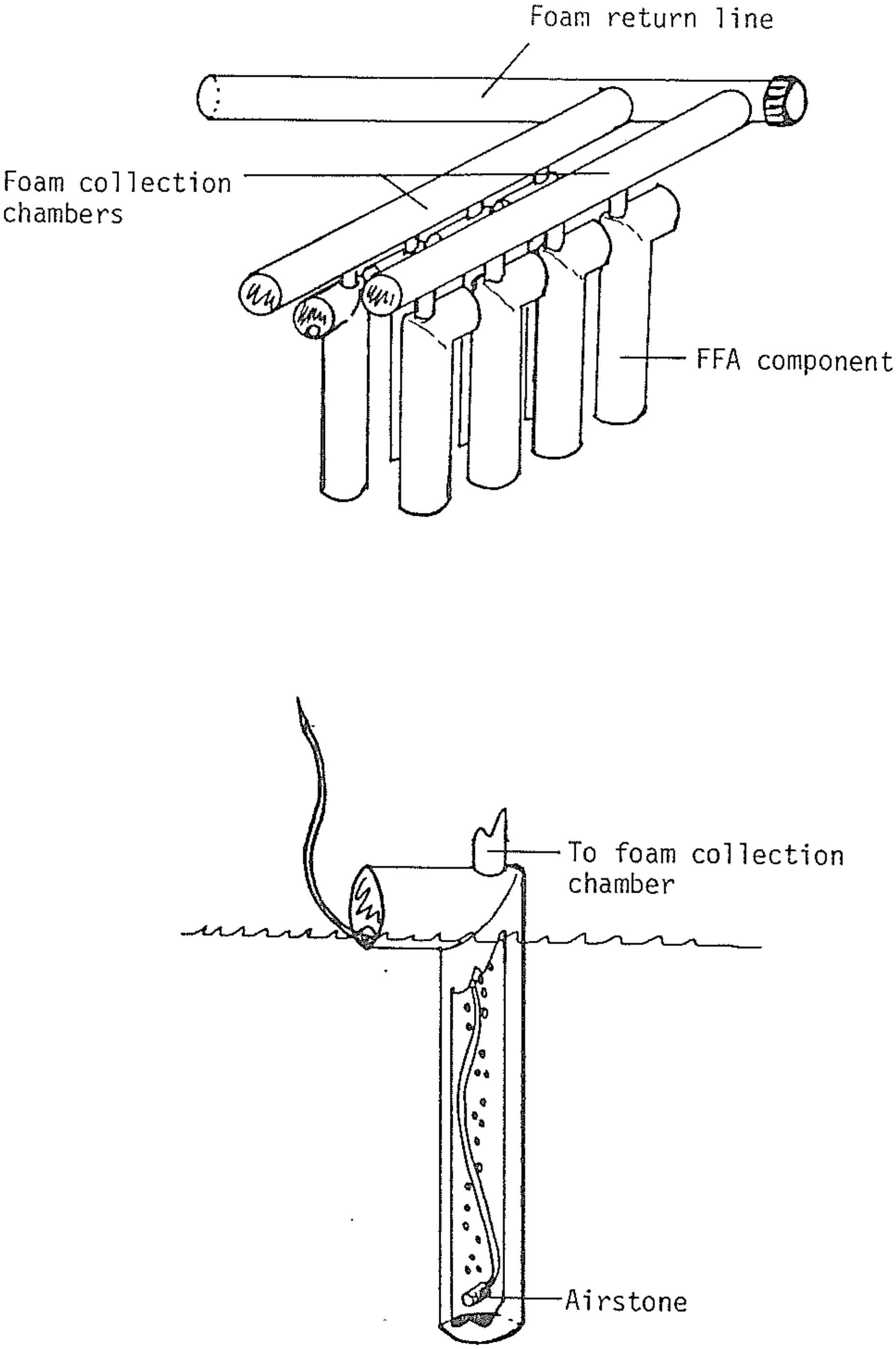

Figure 4. Foam fractionation-aeration unit and component part.

contact column; surface-active materials are adsorbed to the surfaces of air bubbles and non-surface-active compounds are chemically combined to surface active materials. Removal of POC is accomplished by entrapment of particles in foam (Spotte 1979).

Fractionators used in this experiment were of cocurrent design, where air bubbles rise in the column with the flow of water (figure 4). The FFA chamber measured 10 X 24.5 x 16 in. and contained 1.91 ft.^{3} of water. The FFA unit, constructed with 1.5 in. PVC pipe, contained eight FFA components, two horizontal overhead foam collection manifolds and one foam return line (figure 4). Four FFA components attached to each of the foam collection manifolds. Both manifolds attached, perpendicularly, to the foam return line. The two manifolds set side by side; the components on one faced toward, while the components on the other faced away from, the foam return line. Hence, water leaving the components established a counterclockwise flow. Foam in the collection manifolds was carried by gravity flow to the foam return line that routed it past the clinoptilolite filter and deposited it at the underflow headwall of the biofilter for bacterial digestion. The primary function of the FFA unit was to protect the clinoptilotile filter from saturation by DOC and POC, which would render it less effective for ammonia removal. A secondary function was aeration of culture water. Air was diffused in the FFA components by a 1 in. x 0.5 in. diameter airstone. Water free from DOC and POC flowed from the FFA unit into a 2.04 ft.^{3} clinoptilotite filter bed by way of an underflow headwall.

Clinoptilolite is a naturally occurring zeolite earth material that adsorbs ammonium ions (NH_4^+) selectively; it was used as an initial stripper of ammonium ions from effluent water. Clinoptiloite used in this study was obtained from a mine near Buckhorn, New Mexico via donation by the Double Eagle Mining and Petroleum Company of Casper, Wyoming. Chip size ranged from 4 to 14 US mesh. Dust was eliminated by washing.

Water leaving the clinoptilolite filter bed overflowed into a small chamber which served to separate the overflow headwall on the clinoplilotite filter from the underflow headwall by which water entered the biofilter. The biofilter medium was a 0.38 in. volcanic ash rock. This rock contains gas pores, which provide a large surface area for bacterial attachment, and which result in it weighing substantially less than other rock suitable for use in a biofilter. The rock was donated for the study by Morton Brothers-Big Chief Stone of Las Cruces, New Mexico. The function of the biofilter was to convert highly toxic ammonia to less toxic nitrates. The biofilter was innoculated with sheep manure and fish food several weeks before the introduction of catfish. A fine mesh screen (0.06 in.) contained filter media at the underflow headwalls.

Both the clinoptilolite filter and biofilter contained a hydraulic backwash unit, constructed of 1 in. PVC pipe, located on the bottom of the beds (figure 5). Four 6 in. airstones in each filter bed provided continuous air wash to prevent anaerobic activity. When the backwash units were engaged in either bed, in conjunction with increased volume of air to the airstones, the result was a turnover of the filter media. The purpose for this in the clinoptilolite filter was to abraid the chips sufficiently to dislodge ammonium ions (NH_4^+) in small quantities, for oxidation in the biofilter, thus allowing for continuous, inplace recharge of the clinoptilolite. In the biofilter bed, this churning dislodged accumulations of organic material and biotic communities, which then overflowed into the tilapia tank. The FFA unit, clinoptilolite filter and biofilter were contained in the enamel-coated interior shell of an old refrigerator. The tilapia tank was built from the shell of a second refrigerator. Headwalls and dividers were held in place by silicone caulking.

The tilapia tank (45 x 24.5 x 16 in.) contained 8.14 ft.^{3} of water. Eight airlift pumps, 89 percent submerged, circulated water in a counterclockwise direction. A 0.75 in. plywood board painted with epoxy paint, divided the tank in half. However, it did not extend the full length of the tank thereby allowing water to circulate around the ends (figure 6).

The airlift pumps were constructed from 1.5 in. PVC pipe (figure 7). Each of the airlifts had a 12 in. horizontal pick-up pipe (0.5 in. PVC) attached a few millimeters from the bottom of the vertical column. The other end of the pick-up pipe was capped and two rows of perforations along the underside of the pipe functioned to remove water and debris from the bottom of the tank. A 1 in. x 0.5 in. diameter airstone diffused water into the column.

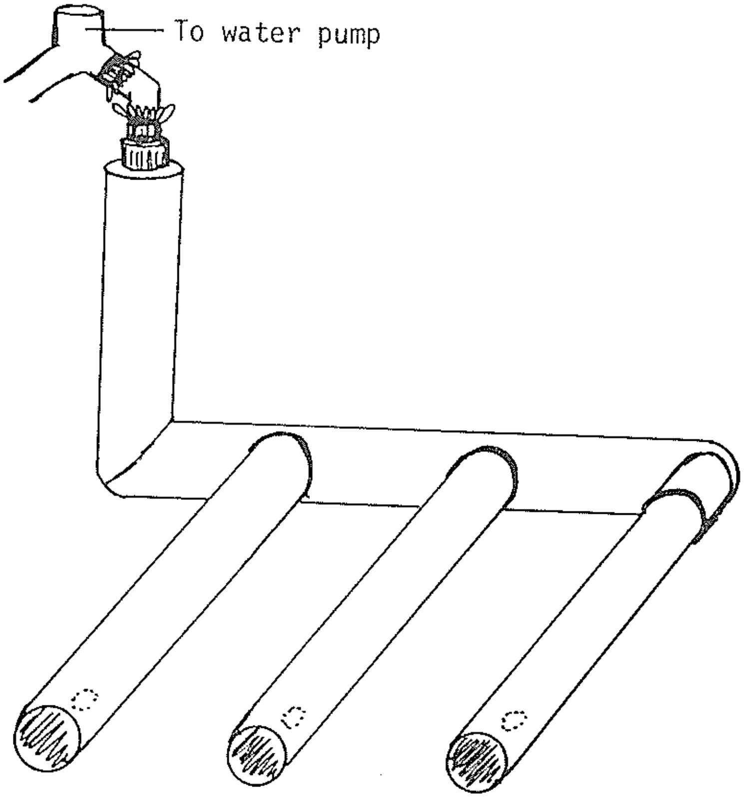

Figure 5. Hydraulic backwash component.

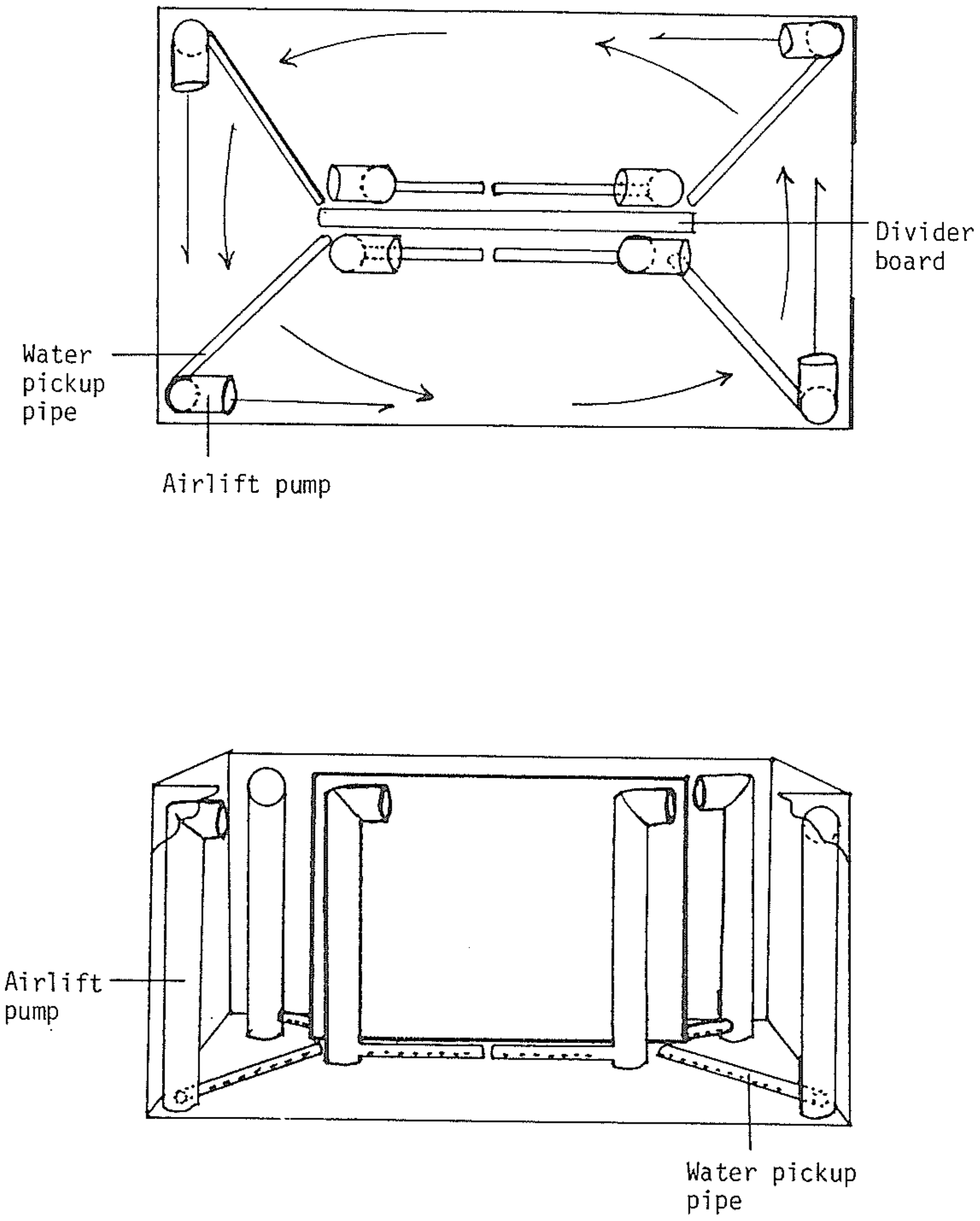

Figure 6. Overview and side view of nutrient recycle tank. Arrows indicate direction of water flow.

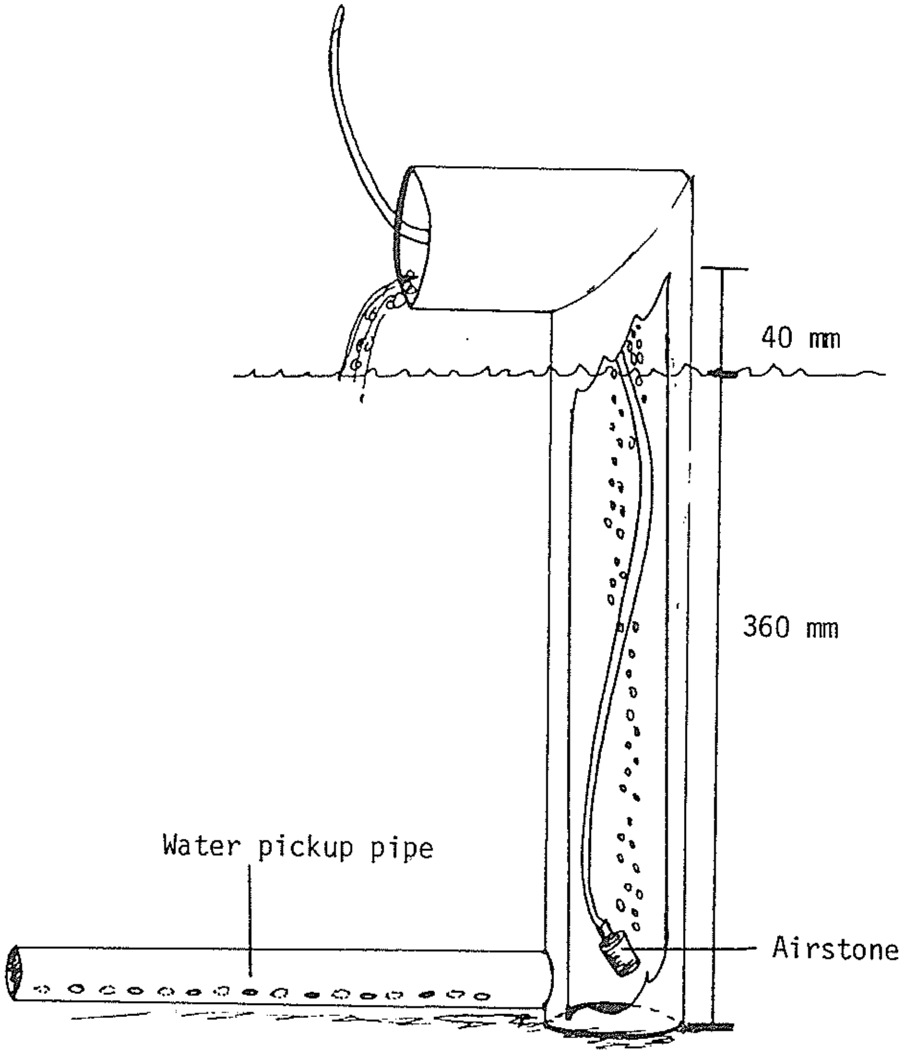

Figure 7. Airlift pump. Percent submergence is 89 percent.

Airlift pumps were positioned (figure 6) based on Hjulstrom young stream building mechanics discussed by Mock et al. (1977). A young stream erodes the bottom and outside banks and turns, with shoaling occuring on inside turns; hence, this positioning placed the pick-up pipes at locations of anticipated sediment buildups.

The tilapia tank also contained tilapia, Tilapia nilotica, alarm activators and a Little Giant dual purpose water pump (500 gal. per hour) which returned filtered water to the vertical raceways. Two Phipps water alarms were used to detect a rise or fall in water level. These alarms were connected to an alarm communicator which, when activated, triggered a beeper alarm carried by project personnel. A 4 ft. fluorescent light fixture with two cool white bulbs was placed above the tank. The light was on for 24 hours per day to stimulate algal growth.

Water leaving the tilapia tank was pumped to the raceway inflow manifold. This rectangular manifold was constructed of 1 in. PVC pipe and had an 18 in. vertical stand pipe at each corner to prevent air-locking. Each raceway was connected to this manifold by a raceway water injector (figure 3). An inline piece of flexible clear plastic tubing allowed for regulation of flow with a screw clamp and for observation of primary producer accumulations, buildups of which would reduce flow. A piece of rigid plastic tubing (0.38 in.) located at the 90° angles of the injector prevented airlocking and, when removed, allowed for removal of primary producers with a laboratory glassware brush. Water was injected into the raceways in a counterclockwise direction through a single line of perforations in a vertical pipe. The end of this pipe was capped so that all of the water was injected horizontally to create a spiral flow for self-cleaning of raceway walls, and to prevent upwelling of settleable solids in the raceway sump.

Air supply for the system was provided by a compressor and by a high volume/low pressure Rotron (DR-101) regenerative blower. A series of valves allowed for use of either the compressor or blower as an air source. Air flow was regulated by small, plastic clamps on the airlines.

The culture system was filled with tap water that contained approximately 400 mg/l TDS. Chemicals were added to this water to obtain a minimum of 3500 mg/l TDS with ionic concentrations similar, proportionally, to that of ground water in the Pecos River Valley. Water lost to evaporation was replaced with tap water; hence, salinity of the culture water increased slowly during the course of the study.

Thirteen of the 15 vertical raceways were stocked with channel catfish; the remaining two were stocked with tilapia, T. aurea. Catfish were continuously added to the raceways to test the effects of increased biomass loading on the system. The tilapia tank was stocked with 51 tilapia, T. nilotica, with a total biomass of 90 g. Their function was to consume plankton and any organic matter entering the tank from the raceway sumps, biofilter, and raceway FFA unit. Fish in vertical raceways were fed once per day with Purina floating trout feed at rates varying from 1 to 3 percent of fish biomass.

A culture of Chlorella pyrenoidosa (UTEX 123) was obtained from the Culture Collection of Algae, University of Texas at Austin. The test system was innoculated with 4 gal. of culture medium containing approximately 3 million Chlorella cells per ml, the purpose of which was control of nitrate and phosphorous levels in the system.

The test system was located in an environmental chamber which maintained an air temperature of 26.7°C, a relative humidity of 100 percent, and a photoperiod of 16 hours (0700-2300). Culture water was maintained at 27.8°C by thermostatically controlled aquarium heaters. Chemical analyses were made at appropriate locations throughout the system on various schedules. Tests conducted with a Hach DR-EL/2 photoelectric colorimeter were ammonia ($NH_3 + NH_4^+$) NO_2^-, NO_3^-, total phosphate, DO, and pH. Ionic concentrations of culture water were determined at the Soil, Water, and Plant Testing Laboratory, New Mexico State University and five day manometric BOD tests were done at the Water Utilities Laboratory, Dona Ana Branch Community College, New Mexico State University. Rates of air flow were measured with a Gilmont by-pass flow meter.

RESULTS AND DISCUSSION

Vertical Raceways

The 15 vertical raceways utilized counterclockwise, spiral flows. One advantage of using vertical raceways is increased production of fish per unit of volume over horizontal raceways (Moody and McCleskey 1978). Also, when water is introduced under pressure, aeration occurs as water is circulated around the vertical raceway. As a result, a buildup of ammonia will often be the first limiting factor to fish production (Piper et al. 1982; Larmayeux et al. 1973). Advantages of spiral flow patterns are: (1) lower current velocities for fish to oppose, which results in uniform distribution of fish in the raceway, (Leitritz and Lewis 1976); (2) uniform distribution of oxygen; (3) less interference with sinking of settleable solids; (4) minimized turbulence; (5) minimized friction at the shearing plane; (6) minimized upwelling at the top of hydraulically dead space; (7) and a self-cleaning system (Slone et al. 1981).

Spiral-flows in the 15 vertical raceways on the test system were erratic. Water was injected through a single line of perforations in a vertical pipe, which should establish a spiral flow, however, several factors prevented this from occurring. Water was not injected under sufficient pressure to establish a strong initial velocity. A much stronger force setting water in motion in the raceways was the FFA component. Water exiting the FFA component would strike the side of the raceway causing water to move in both clockwise and counterclockwise directions. Another factor was the raceway sump. If a sump was clogged, a stronger upward-spiral resulted because water drained only from the overflow drain pipe near the top. If the sump was not clogged water drained from both bottom and top causing a division in spiraling action. Hence, raceways contained clockwise, counterclockwise and nondirectional flows and erratic, unpredictable spiraling action. Given these conditions, it was not possible to measure current velocities in the raceways. Only two of the raceways were self-cleaning, these contained tilapia, <u>S. aurea</u>, which kept the sides of the raceways clean by continuously grazing on buildups of primary producers.

The quantity of water entering individual raceways was highly variable even when screw clamps were used to regulate flow. Total water leaving the raceways through overflow pipes and sumps was 6.69 gpm. When sump drain lines were not clogged, water from the sump line manifold flowed into the tilapia tank at a rate of 2.97 gpm. When all sump lines clogged, overflow pipes at the top of the raceways were sufficiently large to drain the additional water; therefore, water entering the filtration beds would vary between 3.71 gpm to as high as 6.68 gpm dependent upon the numbers of clogged sump drain lines. A somewhat crude estimate of time for exchange of raceway-volume was 8.3 minutes. Make-up water for evaporation loss was 2.39 gal per day. Despite frequent clogging, sumps effectively collected settleable solids from the raceways and flushing twice per day prevented solids from upwelling due to fish activity.

Foam Fractionation - Aeration Unit

The FFA components operated at 100 percent submergence and required a mean air volume of 54.69 (sd = 0.88) liters per minute (lpm) of compressed air; a volume which resulted in a flow of 0.17 gpm of foam and water exiting the FFA foam return line.

Airlift pumps in the tilapia tank, FFA components in the raceways, and the FFA unit required compressed air to operate properly. Airlifts in the tilapia tank had to lift water 1.5 in. above the surface level of water in the tank. Foam and water in the vertical raceways and FFA unit had to be lifted 3.5 in. from the water surface to the foam collection chambers. The Rotron regenerative blower provided an adequate volume of air but lacked sufficient pressure to lift foam and water to the required heights; however, a system designed to incorporate a regenerative blower for aeration would have a cheaper, more efficient source of air than could be obtained from a compressor.

The FFA unit appeared to function well at moving POC past the clinoptilolite filter as indicated by a large buildup of organic floc in the chamber which separated the clinoptilolite bed from the biofilter. So much particulate matter was deposited at the underflow headwall to the biofilter that it soon became clogged causing surface flow of effluent water across the biofilter bed. This problem was solved by stocking 8 *T. aurea* in the separation chamber. Within three days these fish had consumed all of the particulate buildup and effectively prevented additional deposits. Tilapia feces were not a problem in preventing underflow of water into the biofilter. It was not possible to determine the effectiveness of the FFA unit for protecting the clinoptilolite filter for reasons discussed under Clinoptilolite.

Clinoptilolite

There are three principal methods of removing ammonia from waste water: (1) ion exchange; (2) biological nitrification; and (3) air stripping at high pH (Reeves 1972). The latter method is not compatible with fish culture.

Clinoptilolite adsorbs ammonium ions selectively in fresh water even in the presence of competing ions such as Mg++, Ca++ and Na+ (Mercer and Ames 1978). Johnson and Sieburth (1974) found that the presence of a salinity of 5 percent of artificial water (ASW) (1750 mg/l TDS) reduced the ammonia removal efficiency of clinoptilolite tenfold. Salinities of 10, 15 and 25 percent ASW (3500, 5250 and 8750 mg/l TDS, respectively) reduced efficiency even more but not as dramatically as the initial decrease which occurred at 5 percent. It was ineffective in sea water. Clinoptilolite would function, to a limited extent, within the range of salinities reported by Turnbull (1984) as acceptable for culture of channel catfish in the Pecos River Valley of New Mexico. The clinoptilolite filter in the test system did not remove measurable quantities of ammonia from effluent water because the small screen at the underflow headwall and the relatively small size of the chips resulted in a resistance to water flow. This caused water to overflow the headwall, move across the surface of the filter bed, and flow directly into the biofilter. Six *T. aurea* were stocked in the FFA unit in the event that organic floc was clogging the underflow screen, but no alteration in flow pattern was dicernable after several days. Because removal and replacement of the too small screen and increasing the height of the headwall would have required complete draining and disassembly of the system, no further attempt was made to rectify the problem. A test with malachite green dye at the end of the study confirmed that the majority of water flowed across the surface of the clinoptilolite bed.

It was not determined if the FFA unit functioned effectively to protect the clinoptilolite bed from DOC or POC or if the material could be recharged by abraiding ammonium ions with air wash and hydraulic backwash. Evaluation of these techniques required monitoring of ammonia breakthrough, over time, from the clinoptilolite filter. Because there was no significant difference in ammonia concentration in water flowing into and out of the filter, no comparison was possible. In any case, if this recharge method had worked, it would have been unsuited for incorporation into a production system because it would be illogical to needlessly expose microbiological filters to shock loads of ammonia which can produce lethal nitrite levels (Colt and Armstrong 1981).

A practical application of clinoptilolite to a recycled-water system would be the use of column filters which could easily be isolated and replaced without affecting the operation of the system. This approach would provide a backup system to biofiltration for removal of ammonia in case of biofilter failure, or as an alternative system used while treating parasites and diseases with certain chemicals so as not to harm nitrifying bacteria in the main biological filter (Johnson and Sieburth 1974; Slone et al. 1981).

Biofilter

The most practical and economical method for removing ammonia nitrogen from recycled-water systems is nitrification by chemoautotrophic bacteria in biological filters. In nitrification, NH_4^+ is first converted by *Nitrosococcus* and *Nitrosomonas* to nitrous acid then by *Nitrobacter* to nitric acid. Either acid combines with an available base to form nitrite (NO_2^-) and nitrate (NO_3^-), respectively (Burrows and Combs 1968). The end product of the process is NO_3^- which is relatively harmless to fish. Nitrification is most rapid at pH 7 to 8 and at temperatures of 25 to 30°C (Boyd 1979). The doubling time at 30°C is 13 hours for *Nitrosomonas* and 14 hours for *Nitrobacter* (Colt and Tchobanoglous 1976). Nitrification slows at pH 6.0 and ceases completely below 5.5. However, this low pH does not appear to be toxic to nitrifying bacteria (Haug and McCarty 1972).

During nitrification, 2 moles of hydrogen ions are produced for each mole of NH_4^+ oxidized. Therefore, in an unconditioned and unbuffered system, the flood of hydrogen ions produced in association with the rapid conversion of a high concentration of NH_4^+ to NO_2^-, results in a rapid and marked fall in pH (Collins et al. 1975). Because a properly functioning biofilter will result in a continuous lowering of pH due to oxidation of NH_4^+, a continuous buffering component which would stabilize pH is essential. Burrows and Combs (1968) found that an oyster shell filter bed, which supplies calcium carbonate, ($CaCO_3$), stabilized the pH of recirculating water in a range between 7.8 and 8.0.

Un-ionized ammonia is toxic to fish but the NH_4^+ is relatively nontoxic. The proportion of NH_3 in total ammonia (NH_3 + NH_4^+) is influenced by pH and temperature. The percentage of NH_3 will increase as pH and temperature increase and vice-versa. Knepp and Arkin (1973) reported a LC_{100} to channel catfish of 45.7 mg/l (sd = 6.0 mg/l) and a LC_{50} value of 37.5 mg/l (sd = 1.7 mg/l) total ammonia at a temperature of 22°C and pH of 7.8. These values are equivalent to NH_3 values of 1.28 mg/l and 1.05 mg/l respectively. Colt and Tchobanoglous (1976) reported the 96 hour LC_{50} for NH_3 to channel catfish as 2.4 to 2.8 mg/l at 30°C.

In flow-through systems, ammonia is the principal toxic metabolic by product but in recycled-water systems both ammonia and NO_2 may occur at toxic levels (Colt and Armstrong 1981). Ninety-six hour nitrite LC_{50} for channel catfish has been reported as 24.8 mg/l at 21°C (Konikoff 1975) and 46 mg/l at 30°C (Colt and Tchobanoglous 1976). However, the lethal effects of NO_2^- to fish is extremely variable depending on water chemistry and species (Colt and Armstrong 1981). Nitrate accumulates in recirculating water systems as an end product to nitrification and is relatively harmless to fish. Knepp and Arkin (1973) reported that channel catfish eat and grow normally in waters containing NO_3^- concentrations of 400 mg/l (Colt and Tchobanoglaus 1976) reported LC_{50} concentrations for channel catfish as 6,200 mg/l.

Four, 6 in., airstones supplied continuous air-wash to the biofilter at a rate of 42.6 lpm (sd = 1.67) per airstone. This was adequate to supply oxygen for aerobic activity since no hydrogen sulfide was detected during backwash of the filter bed. During backwash, water flow to the hydraulic backwash unit was engaged and the rate of air flow to each airstone was increased to 59 lpm (sd = 1.41). This dislodged biotic and organic particulate matter buildups in the volcanic-ash rock substrate and flushed them into the tilapia tank. After backwash, settleable solids in this tank increased from less than 0.1 ml/l to 0.54

ml/l (sd = 0.21) indicating effective dislodging and removal of organic matter from the filter by the combined effects of the airwash and backwash units. Backwash activity was conducted for 5 minutes at approximately two week intervals.

Tilapia Tank

Eight airlift pumps operating at 89 percent submergence, moved water around the tank, in a counterclockwise direction, at a velocity of 0.085 fps (sd = 0.01). Airlifts were operated by airstones supplying compressed air at an average rate of 53 l/min (sd = 2.37); average volume of water pumped by each airlift was 1.27 gal/min (sd = 0.19). The complete volume of water contained in the tank flowed through the eight airlifts approximately every 6 minutes. Average volume of settleable solids in the tilapia tank after flushing of sumps was 0.42 ml/l (sd = 0.08).

The positioning pattern of the pick-up pipes on the airlifts (figure 6) proved to be very efficient. Tilapia rapidly consumed nearly all settleable solids that were flushed into the tank; therefore, the only solids present in significant amounts were "strings" of tilapia feces. These "strings" were effectively removed from the bottom of the tank by the pick-up pipes and tended to accumulate on the air hose lines at the point where water exited from the airlifts. These fecal accumulations supported dense growths of algae and decomposed rapidly. It appears that algal-coated, semi-decomposed feces was consumed by tilapia, because the feces did not accumulate in the tank.

A four-foot fluorescent light fixture with two cool white bulbs was suspended just above the tank to stimulate algal growth. The Chlorella did not establish a population in the culture system, presumably because of insufficient light, water quality, or a lack of required nutrients. The most abundant organisms in the culture water were bacterial cells, 2-3 um in diameter, with an estimated density of 50 thousand cells/ml. Total algal concentration, which did not include Chlorella, was less than 1000 cells/ml. Other organisms were protozoans and diatoms present in very low concentrations.

The tilapia tank was stocked with 51 T. nilotica which weighed a total of 90 g. At the end of the study, 56 days later, the 51 tilapia weighed 780 g, an increase in weight of 870 percent. The tilapia consumed algae attached on the sides of the tank and just above the water line. These fish also fed on material flushed in from the biofilter, and as their primary food source, catfish feces and uneaten feed from the vertical raceway sumps. The ammount of uneaten feed consumed by these tilapia during the study period was estimated at 568 g.

Alarms were frequent until the activators were adjusted to proper levels in the tanks. When adjusted, the alarm system was sensitive enough to detect the complete emptying of a single raceway or a drop of 0.5 in of water in the tank. The most frequent cause for a legitimate alarm was the draining of raceways due to improper adjustment of sump clamps after flushing. Several alarms resulted from fall in water level due to buildup of water in raceways caused by dead fish plugging overflow drain holes. Only one false alarm occurred during the study, presumably because someone mistakenly dialed the telephone number that triggered the beeper.

Water Quality

Culture Water. Tap water used to fill the test system and to replace evaporation loss contained approximately 400 mg/l TDS (table 1). An attempt was made to achieve 3,500 mg/l TDS, with ionic proportions similar to those in Roswell city water, by addition of the following chemical compounds: $MgSO_4$, 517.10g; $CaSO_4$, 726.41g; $CaCl_2$, 310.88g; NaCl, 348.16g; and Na_2CO_3, 471.28g. The result was a salinity of 3,240 mg/l TDS with the ionic proportions between the culture water and Roswell city water being greatly dissimilar but well within the range of possiblity for groundwater in the Pecos River Valley.

At the end of the study, TDS of culture water had reached 4060 mg/l (table 1). A major source of variation in ionic concentration was the 3.29 gal/day of tap water used to replace evaporation loss. Daily ionic composition of this water was dependant upon which combination of several wells was used to supply tap water to the laboratory on that particular day. Hence, salinity increased steadily during the study but there was no control over the quantity or proportion of ions added.

One concern about using New Mexico groundwaters for aquaculture is the potentially damaging effect of high levels of sulfate ions ($SO_4^=$) to cultured species (Turnbull 1984). Turnbull found that $SO_4^=$ levels greater than 800 mg/l caused reduced growth and poor food conversion in channel

TABLE 1

CONCENTRATIONS OF VARIOUS IONS IN CULTURE WATER.

Constituent	Roswell City Water*	NMSU Tap Water	After Chemical Addition	End of Study
Na	215.0	44.0	569.6	635.1
K	3.2	--	23.8	59.5
Ca	591.0	58.3	388.8	531.9
Mg	163.9	10.9	88.5	113.8
CO_3	--	0	0	0
HCO_3	764.9	162.3	128.1	24.4
Cl	311.8	48.6	741.0	770.9
SO_4	1449.5	76.0	1300.0	1925.0
TDS	3499.3	400.1	3239.8	4060.2

*Ionic concentrations increased proportionally from 1089 mg/1 to 3500 mg/1.

Source: S. Isaacs, Chemist, Roswell Test Facility; tested December 20, 1983.

catfish. Sulfate levels in the present study ranged between 1,300 and 1,925 mg/l or 40 and 47 percent, respectively, of total salinity. Even so, _T. aurea_, doubled their initial weight (see Vertical Raceway Fish Culture) and the initial weight of _T. nilotica_, increased by 870 percent during the study. Tilapias are euryhaline, and apparently tolerant to high concentrations of SO_4^-, thus demonstrating a great potential for culture in brackish waters found in New Mexico.

Nitrogen. During the 56 days that fish were in the test system, ammonia concentrations fluctuated but increased steadily in conjunction with continuous additons of catfish biomass. On the last day of the study, total ammonia reached its highest level of 4.49 mg/l, or an NH_3 concentration of less than 0.03 mg/l at 28°C and pH 6.5. Total ammonia levels were typically less than 2 mg/l throughout the study, and the highest concentration occurred after an addition of catfish that brought the total biomass of fish in the system to 17.2 kg. Catfish were added continuously over a short period of time to simulate fish growth in order to test the filtration components of the system. Even though ammonia concentration remained at acceptable levels, they probably were atypical of a system in which fish biomass resulting solely from growth is added more slowly.

Nitrite concentration in the system was typically less than 1.0 mg/l; however, a high of 3.03 mg/l was reached toward the end of the study. This peak followed by a decline probably occurred as a result of a mild shock load of ammonia to the biofilter caused by addition of catfish biomass.

Increase of NO_3^- was initially slow, followed by a rapid increase to a peak of 240 mg/l by the end of the study. Because a phytoplankton community was not well established in the system, any recycling of NO_3^- occurred in the biofilter, in periphyton communities or in the clinoptilolite bed, which could have functioned to some degree as a biofilter. Undoubtedly, a major source of NO_3^- was settleable solids that eventually contributed to NO_3^- concentration by way of ammoniafication and nitrification. In a recycled-water system such as this where settleable solids are not completely removed from the system, it is likely that toxic concentrations of NO_3^- could be achieved in a relatively short period of time.

pH. The range of pH in the test system began with a high of 8.5 early in the study and ended with a low of 6.4 when nitrification was well established. Five days before the end of the study, 100 g of sodium bicarbonate was added to the culture water to forstall any farther reduction in pH. This action increased pH to 7.4; however, at the end of the 5 day period, pH was once again at 6.4. Hence, a continuous buffering component is needed for long term operation of a recycled-water system.

Phosphorus. Measurements of total phosphorus in the test system were erratic and widely fluctuating. Concentration increased from 2 mg/l up to 4.9 mg/l in two weeks, down to 1.5 mg/l in one week and then back up to 4.5 mg/l in nine days. It was assumed that old chemical reagents accounted for this wide range of variation.

Biochemical Oxygen Demand and Dissolved Oxygen. Five-day BOD was analyzed in the system at the raceway effluent manifold, the underflow headwall into the biofilter, the overflow headwall from the biofilter, and the tilapia tank. Halfway through the study, when fish biomass was 4.2 kg., BOD levels were 3.5, 2.3, 1.1 and 2.0 mg/l, respectively. At the conclusion of the study, when fish biomass was 17.2 kg, BOD levels had increased to 22.2, 16.5, 25.0 and 20.6 mg/l, respectively. Slone et al. (1981) found that highest levels of BOD, 300 mg/l and 240 mg/l, occurred in the bottom of a remote settleable solids sump and in a vertical raceway sump, respectively. The average BOD in the remainder of their system was 12.5 mg/l. They concluded that removal of settleable solids by sump flushing effectively removed BOD from the system. BOD occurred at relatively low levels in the current test system as a result of adequate aeration and consumption of settleable solids by tilapia. However, consumption of settleable solids by tilapia did not constitute complete removal of the solids from the system, therefore, it may be assumed that BOD in this system would have continued to increase over time.

Aeration was provided in the system by 39 airstones that were dispersed throughout the system. When fish biomass was 10.9 kg or less, and BOD ranged between 1.1 and 4.2 mg/l, DO was maintained between 6 and 7 mg/l at a water temperature of 27.8°C. At this same water temperature, DO decreased to a range of 5 to 6 mg/l when fish biomass was between 10.9 and 17.2 kg and BOD was increasing.

Vertical Raceway Fish Culture

Channel catfish and tilapia were in the test system for 56 days. Growth of fish in the vertical raceways was not an objective of this study, rather, the effects of fish biomass on the system components was of primary importance.

Catfish biomass in 13 of the raceways was steadily increased, as water quality permitted, using reserve stock, and a small amount of growth did occur (table 2). A total of 521 catfish weighing 14,515 g were stocked during the course of the study and 452 fish weighing 15,987 g were removed at completion; a net loss of 69 fish but a net gain of 1,472 g in weight. Thirty-three fish weighing 587 g were either found dead or had jumped from raceways into the filtration unit. The remainder were accounted for by accumulations of bones found throughout the system. Catfish were fed once per day at rates varying from 1 to 3 percent of fish biomass, dependent on water quality parameters and fish behavior. The fish were very skittish, apparently due to transparent raceways and continuous stocking, therefore consumption of feed was very erratic and unpredictable. Total amount of feed given to catfish during the study was 5.6 kg, approximately 10 to 15 percent of which was flushed into the tilapia tank.

Two of the raceways were stocked with a combined total of 87 *T. aurea* which weighed 165 g (table 2). These tilapia suffered no mortality and more than doubled their initial weight in 56 days. These fish were fed once per day, at a rate of 3 percent of fish biomass, and weight gain might have been greater but several tilapia in each raceway were too small to consume a food pellet in one bite; therefore, larger tilapia consumed the majority of food each day. Nevertheless, combined weight gain for the two raceways was 225 g and total weight of feed added was 138 g giving a crude feed conversion rate (weight of feed fed/weight of fish produced) of 0.61.

The averge weight of catfish, in the 13 raceways, at the end of the study was equivalent to 5.4 lbs of fish biomass per $ft.^3$ of water in the raceways. Total weight of all fish in the system was equivalent to 1.6 lbs. of fish biomass per $ft.^3$ of culture water. At this point, the system had probably achieved, or was fast approaching, maximum biomass loading as indicated by increasing concentrations of ammonia, NO_2^-, NO_3^-

TABLE 2

SPECIES, NUMBERS, AND WEIGHTS OF FISH IN 15 VERTICAL RACEWAYS AND TILAPIA TANK.

Raceway	Species	Total Number Stocked	Total Weight Stocked (g)	Total Number Harvested	Total Weight Harvested (g)	Net Change Number	Net Change Weight (g)
1	Channel catfish	38	1125	34	1142	- 4	+ 17
2	Channel catfish	39	1070	36	1275	- 3	+ 205
3	Channel catfish	39	1120	34	1365	- 5	+ 245
5	Channel catfish	39	1030	35	1255	- 4	+ 225
6	Channel catfish	40	1150	34	1320	- 6	+ 170
7	Channel catfish	43	1195	37	1360	- 6	+ 165
8	Channel catfish	39	1145	29	965	-10	- 180
10	Channel catfish	38	1070	36	1280	- 2	+ 210
11	Channel catfish	42	1150	35	1130	- 7	- 20
12	Channel catfish	38	1130	32	1150	- 6	+ 20
13	Channel catfish	40	1070	35	1140	- 5	+ 70
14	Channel catfish	40	1100	34	1240	- 6	+ 140
15	Channel catfish	46	1160	41	1365	- 5	+ 205
	TOTAL	521	14515	452	15987	-69	+1472
4	*T. aurea*	46	80	46	190	0	+ 110
9	*T. aurea*	41	85	41	200	0	+ 115
	TOTAL	87	165	87	390	0	+ 225
Tilapia tank	*T. nilotica*	51	90	51	780	0	+ 690
	TOTAL	51	90	51	780	0	+ 690

and BOD. Slone et al. (1981) reported 10 lbs./ft.^{3} in a vertical raceway; however, that system provided for removal of settleable solids and the current test system merely transferred solids from one location to another. While a good deal of these solids were converted into tilapia flesh and not BOD, this did not constitute complete removal from the system and a gradual degradation of water quality resulted. To achieve a greater biomass of fish/ft.^{3} it is necessary to flush settleable solids from the primary culture system to avoid eventual buildup to toxic conditions. Settleable solids could still be used to feed tilapia but these fish should be maintained in a seperate, secondary culture system.

Overall, the test system was too complex, expensive to operate, and was dependent on too much compressed air and airlift circulation. The system contained too many subsystems (FFA components in raceways, FFA unit, tilapia tank) which were added to correct two major flaws; sumps did not flush settleable solids out of the system and the sequence of the clinoptilolite filter and biofilter was reversed.

A system tested by Slone et al. (1981) had the biofilter placed before the clinoptilolite filter with good results. Using this sequence the clinoptilolite was effectively protected from POC by the biofilter. Thus, the clinoptilolite had to remove only the breakthrough ammonia from the biofilter and remained effective for ammonia removal for a longer period of time. Additionally, settleable solids sumps that flushed waste material outside of the culture system, in conjunction with a biofilter, effectively controlled ammonia, POC, uneaten feed, feces, phosphorus, NO_3^-, and settleable solids.

In the current test system the addition of the raceway FFA components, FFA unit and tilapia tank did not contribute to the control of these problems. These subsystems do not enhance a basic culture system which contains a vertical raceway, remote settleable solids sump, biofilter, and a clinoptilolite filter as a backup to biofiltration for ammonia removal.

PRINCIPAL FINDINGS AND RECOMMENDATIONS

Principal findings were:

1. Vertical raceways with remote settleable solids sumps are desirable components in a recycled-water, fish production system. A 600-800 gal. circular tank with a remote settle-

able solids sump constructed of 12 in. diameter PVC pipe might be suitable for fish culture purposes.

2. The use of underflow headwalls as the means by which effluent water entered the filter beds rendered the clinoptilolite filter useless and restricted the effectiveness of the biofilter. In spite of this design problem, the biofilter functioned adequately for ammonia removal. Both the clinoptilolite and biofilter material would be more effectively employed in a culture system if they were contained in an upflow column constructed from 12 in. PVC pipe. The bottom of each filter column would function as a second level sump for removal of settleable solids from the system. This secondary sump would allow for removal of any settleable solids not removed by the primary sumps and also would prevent clogging of the filter materials. A filtration component of this type should allow for easy isolation, removal, replacement and addition of columns without affecting the functioning of the overall culture system.
3. Efficient removal of ammonia by nitrification resulted in a predictable decrease in pH, therefore, a continuous buffering component for stabalization of pH is required. Suitable buffer materials are oyster shells, limestone or other sources of calcium carbonate.
4. An alarm component capable of detecting change in water level is essential in a culture system. The presence of an alarm on the test system prevented loss of fish on many occasions.
5. In recycled-water systems a polyculture approach to fish production is desirable. In the test system, biomass of tilapia, <u>T. nilotica</u>, increased by 870 percent in 56 days. These fish were fed only catfish feces and uneaten feed flushed from raceway sumps. Tilapia are euryhaline and tolerant of high sulfate ion levels, thus they have a tremendous potential for increasing overall biomass production in a brackish water culture system by utilizing settleable solids flushed from catfish raceways as a food source.

6. Subsystems such as FFA components and the tilapia tank are energy consumptive and do not enhnce a basic culture system which contains a vertical raceway, remote settleable solids sump, biofilter, and clinoptilolite filter as a backup to biofiltration for ammonia removal.

Recommendations for additional research are:

1. Analysis of production size culture system operational costs to determine areas of economic liability.
2. Identification of maximum stocking rates compatible with optimum growth of cultured species.
3. Identification of optimal ratios of biofilter volume to fish biomass.
4. Development of a fish grading component.
5. Determine usefulness of waste products from fish culture for producing additional crops such as algae, hydroponic vegetables, or other biological products with economic value.
6. Development of brood-fish components for egg production to provide a continuous in-state source of fish for culture.
7. Identification of additional species suitable for integration into a polyculture system.
8. Analysis of public consumption and marketing patterns of such crops and species as are suitable for integration into a culture system.
9. Develop methodology for operating an integrated, multiple-crop, production system in a greenhouse environment.

SUMMARY

* Seventy-five percent of the groundwater in New Mexico is too brackish for use in producing conventional agricultural crops. Some of this water is suitable for aquacultural purposes; however, erratic temperatures of groundwater and evaporation are major problems that must be solved.
* Intensive, indoor recycled-water systems may provide solutions to these problems. The systems require control of settleable solids, toxic gases, dissolved oxygen, nitrogenous wastes, and pH.
* A recycled water system was studied to help find solutions to these problems.
* Biofiltration was effective for converting toxic ammonia and nitrite to relatively non-toxic nitrate. This process requires a buffering component to stabalize pH. Ideally, nitrate can be removed from a system by biofiltration and flushing settleable solids from remote sumps.
* Clinoptilolite was ineffective for ammonia removal in this study due to design problems; however, redesign of filtration components would allow for the use of this material as a backup filter to biofiltration. Clinoptilolite would also be useful as an ammonia remover in systems which are being treated with parasiticides and bacteriacides which are potentially harmful to nitrifying bacteria.
* An alarm system to detect a change in water level in a culture system is essential.
* Tilapia, _T. nilotica_, in the test system effectively utilized settleable solids flushed from raceway sumps as evidenced by a biomass increase of 870 percent in 56 days. Consumption of these solids by tilapia maintained biochemcial oxygen demand at relatively low levels by converting potential BOD producing settleable solids into fish flesh. A secondary tilapia system which operates independently of the primary system is most desirable.
* Biomass of tilapia, _T. aurea_, doubled, in 56 days, in two of the vertical raceways on the holding system. This increase was indicitive of weight gain by a few large fish and did not represent uniform growth of all individuals. A fish grading component to put

fish of uniform size in the same tank could result in more uniform fish growth.

- Channel catfish biomass in vertical raceways on the test system reached 5.4 lbs./ft.^{3} of raceway culture water. This biomass could be increased with more efficient filtration and complete removal of settleable solids to a secondary system containing tilapia.
- A desirable, recycled-water fish culture system is one which contains a vertical raceway, a remote settleable solids sump, a biofilter, and a clinoptilolite filter which serves as a backup to biofiltration for ammonia removal.

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