WRAC PROJECT TERMINATION REPORT

PART I: SUMMARY

PROJECT TITLE: Reducing Phosphorus Discharge from High Density, Flow-through Aquaculture Facilities

PROJECT WORK PERIOD: 3/15/00 - 4/16/04

AUTHOR: Shulin Chen, Work Group Chair
Bill Johnson

PARTICIPANTS:

Shulin Chen	Washington State University	Washington
Kevin Fitzsimmons	University of Arizona	Arizona
Raul Piedrahita	University of California, Davis	California
Gregory Moller	University of Idaho	Idaho
Ronald Hardy	University of Idaho	Idaho
Frederic Barrows	USDA ARS	
John Colt (Technical Advisor)	Northwest Fisheries Science Center	Washington
Gary Fornshell (Extension)	University of Idaho	Idaho
Mark Daily (Industry Advisor)	Jones Trout Farm	Idaho

REASON FOR TERMINATION: END OF FUNDING

PROJECT OBJECTIVES

The goal of this project is to reduce the discharge of all species of P from high-density, flow-through aquacultural facilities with an emphasis on investigating the fate of P and solids between the point of particle introduction into the water and the point of removal. Specific objectives include: 1) Determine the fate of particles in raceways, including transport and breakdown; 2) Investigate the rate of excretion of dissolved P from fish and the rate of release from fecal particles in raceways; 3) Design and evaluate scrap iron granule reactors for removing dissolved P; 4) Improve fecal pellet stability and minimize P loss through feed manipulation; 5) Develop best management practices featuring excretion reduction and efficient removal of both particulate and dissolved P; 6) Evaluate the best management practices in commercial settings

PRINCIPAL ACCOMPLISHMENTS

Objective 1. Determine the fate of particles in raceways, including transport and breakdown

Raceway and particle characterization

Physical dimensions and flow rates of five rainbow trout (*Oncorhynchus mykiss*) flow-through farms in Southern, Idaho, and the effluent of two of those farms were characterized to identify and quantify factors affecting phosphorus (P) discharge. The results indicated that the mean water current velocities in raceways were an order of magnitude below the 0.1-0.6 m/s range recommended to prevent solids settlement (Boersen and Westers, 1986; Alley, 2000), and thus lead to waste settlement in the rearing areas of raceways. The average measured solids settling velocities were 0.16 cm/s and 2.31 cm/s for particles smaller and larger than 814 µm, respectively. The mean particulate P discharge was 0.04 mg/L; composing 3.4% by mass of the discharged suspended solids and representing 40% of total P discharge. The mean dissolved P discharge was 0.06 mg/L representing 60% of the total P discharge. No significant statistical difference was found in P contents associated with different particle size (P>0.11). The average concentration of suspended solids that were greater than 10, 53, and 105 µm were 1.93, 1.34, and 1.01 mg/L, respectively; suggesting that 69% of discharged solids mass was greater than 53 µm and 52% was greater than 105 µm. Laser diffraction particle size analysis revealed a volumetrically weighted median effluent particle size of 250.1 µm; with 89% of the discharged particles larger than 53 µm and 76% greater than 105 µm. The results suggested that the removal of particles over 100 µm from the effluent would result in approximate total P discharge reductions of 20%. Overall, the results confirmed that transport and removal are important factors affecting P discharge.

Hydraulic modeling taking into account sediment transport

Furthermore, a hydrodynamic simulation model for raceway design and management was developed. The model was used to study solid settling patterns in the quiescent zones (QZ) of simulated raceways and to identify ways in which the raceways could be modified to obtain improved settling in the QZ. The model was created using the software package Sediment Simulation In Intakes with Multiblock option (SSIIM). The model includes hydrodynamic and sediment transport components and has been used to analyze the potential impact of QZ modifications on the efficiency of sedimentation within the QZ of six groups of particles with mean settling velocities of 0.01 to 3.9 cm/s. This efficiency was estimated as the percentage of solids removed (PSR), which corresponds to the fraction of the solids introduced into the raceway (TSI) that settle in it.

In addition to obtaining the PSR results, an analysis of the sediment flux contours was conducted to identify the areas where most of the solids tend to settle. Six particle groups were considered for the simulation ranging in size from 692 µm to 35 µm, with group 1 being the largest. The settling space characteristics are similar for particle groups 1, 2, and 3, where the particles settle very close to the point of release due to their high settling velocity and relatively low horizontal water velocities. In particular, a large fraction of the Group 1 sediments settled before the QZ but Groups 2 and 3 show more incursion into the QZ due to their lower settling velocities relative to that of Group 1.

Raceway modifications

After analyzing the velocity profiles and sediment fluxes obtained from the model of a "standard" raceway and considering various design constraints, several raceway design alternatives were simulated. Among the design alternatives tested, six designs were chosen for further analysis based on their PSR values. The main feature in all the modifications presented is the addition of a baffle before the QZ or at the entrance of the QZ replacing the screen. The highest simulated PSR was obtained with the combination of a baffle and a screen under the baffle. The improvement of PSR with respect to the original system was especially noticeable for the smaller particles, which corresponds to 204µm, 61µm, and 35µm in diameter, respectively. The overall increase in solids settling in the raceway was minor, with overall PSR increasing from 81.8 % for the unmodified raceway to 91.1 % for Alternative 5, the alternative showing the best performance. Although this is a minor change in the PSR, this translates to an estimated reduction in the solids exiting the raceway of over 1,200 g/d for each raceway as the one analyzed here. This corresponds to a reduction in solids in the effluent of over 2 % of the amount of feed applied to a raceway.

Q-zone: sizing and cleaning frequency

The evaluation of q-zone sizing on solids and P removal was conducted by combining experimental particle size distribution (PSD), total phosphorus (TP), and total suspended solids (TSS) data with a numerical analysis using Stoke's law for discrete particle settling. Results of the analysis revealed that as the q-zone size increases, smaller sized particles can be removed. Increasing the q-zone length from 1 m to 5.3 m leads to a decrease in particle size, TSS and P discharged, indicating a decrease in the average captured particle size from approximately 680 to 280 µm. This range corresponds to largest, most easily settled particles in the distribution as well as those containing the most mass. The corresponding TSS discharge change would be from 2.2 to 1.7 mg/l and a reduction in P discharge of 36%. However this effect does not remain linear as the q-zone is lengthened, because reductions in captured particle size are now in the relatively smaller size portions of the distribution, less than 280 µm. Substantially higher numbers of these harder to capture particles must be intercepted to equal the mass of a few larger particles so the "rate of return" is decreased in capturing this material by means of settling. An increase in the q-zone size from a hypothetical 1 m to the current 5.3 m decreased P discharge by 36%, while an additional yet equivalent increase to 10.6 m reduced discharge by only 12%. This analysis has provided some important insights. In particular, at this facility and with these experimental numbers, capturing the target 100 µm particles would require more than the entire raceway length (approximately 24 m).

Because of the dilute nature of effluent at these facilities it is often difficult to observe significant changes in water quality measurements. This necessitates a well thought out procedure to evaluate the effect of q-zone cleaning frequency. A procedure was developed and tested in the field. The procedure was performed during the August 2003 field trip, at study site 4 in Southern Idaho, and was able to effectively collect deposited solids over a known area. The procedure will be utilized in continuing research concerning q-zone cleaning frequency and continued improvements in best management practices for the industry.

In order to determine the optimal cleaning frequency of the q-zone, a priority has been placed on the development of a phosphorus (P) release model in the q-zone. The model developed is specific to P exchange at the sediment-water interface. The aim is to simulate the sink and supply of P in the Q-zone. The model was developed by analyzing P transformation in the q-zone and developing a mass balance P transfer model that includes P fate and routing routines. The model will be modified and validated in the field under commercial farm conditions with continuing research funded through the Washington-Idaho Aquaculture Initiative.

Objective 2. Investigate the rate of excretion of dissolved P from fish and the rate of release from fecal particles in raceways

Experiments were conducted in Idaho and Arizona examining the relationships between particulate transport and phosphorus release. Various temperature and water flow rates were tested to determine which factors might influence the rate at which phosphorus was leached from fecal pellets. The trials demonstrated that the rate at which phosphorus leached was not measurably influenced by water motion, between 0.027 m/s and 0.134 m/s. Nor was it influenced by temperatures within the range of 14^{o} and 19^{o} C. The basic conclusions we have reached are: 1) Phosphorus begins to leach immediately from feces after they are expelled. This seems to be more a physical-chemical reaction rather than a bacterial reaction; 2) The rate is not affected by the velocity of water flow or temperature; 3) Rapid removal of feces from the system will provide the best reduction in the amount of phosphorus in the effluent.

Objective 3. Design and evaluate scrap iron granule reactors for removing dissolved P

The work product is the development of a process for removal of low level P from discharge waters. A patent application has been filed by the University of Idaho for this technology and it has been licensed for commercialization to Blue Water Technologies. Dosing trials, mechanistic analyses, and 24-hr stability field test with P laden discharges indicate a stable, high efficiency process that is resilient to changing input P levels and small (<1mm) particulates in the influent water. Solids produced by the process are a low grade, slow-release P fertilizer. Field test suggest that 1,000 μg/L total P inputs into the process can be reduced to <50 μg/L in a rapid (9 minutes) small footprint process. Conservative engineering economic analyses using EPA water treatment models suggest total costs of operation of $0.44 per 1,000 gal in larger implementations. This is less expensive than other technologies that operate with less removal efficiency. The high efficiency of removal suggests discharge water blending is appropriate in many applications. Conclusive field tests at Thousand Spring aquaculture facilities and the tertiary discharge of the City of Moscow wastewater treatment plant indicate that removal to low total P levels is possible even for process influents in the range of 2,000-5,000 μg/L. We have augmented the process with a novel micro-particulate agglomeration pre-reactor (MPAR) to further assist in particulate and total P removal. We are not aware of any other pilot-scale process, research grade or commercial, with this capability. In the mechanistic analysis, the formation and renewal of iron-oxide coated sand (IOCS) is shown as an active mechanism of multiphase P removal. In related work, we developed an advanced total P analytical methodology to allow for 1 μg/L total P sensitivity in our test waters.

Objective 4. Improve fecal pellet stability and minimize P loss through feed manipulation

The purpose of this component of the project was to determine if inclusion of dietary binders could increase the efficiency of fecal collection before the effluent water is released. A study conducted earlier in this project determined that the inclusion of specific binders in the feed would increase the average size of the fecal pellets. However, it was also noted that fecal size and the density of the fecal pellet may not be related. That would mean that the larger fecal pellet may not settle out of the effluent water more efficiently than the smaller pellet.

To measure the effect of dietary binders on fecal density, a fecal sedimentation tank was designed, manufactured and installed. Three experimental diets, containing different lipid based binders, have been tested using a Latin square treatment design with four replicates per treatment. This study indicates that substitution of a portion of the fish oil with poultry oil in the diet of rainbow trout will increase fecal density and improve recovery of solids in the quiescent zone of raceways.

Objective 5. Develop best management practices featuring excretion reduction and efficient removal of both particulate and dissolved P

New ideas proposed by the research team and tested for development of best management practices for solids removal were the use of a baffle to facilitate particle transport, to extend the weir length of the quiescent zone to enhance particle removal efficiency, and to utilize a low cost high-rate filter media to capture solids escaping the q-zone.

Moving Baffles

The research team at WSU has developed a baffle that will, through flow velocity enhancement, sweep the collected solids from the rearing area for disposal to the quiescent zone, by moving along the raceway via the hydraulic pressure of the flow through system itself. Once the baffle has reached the end of the raceway, engineering designs will allow for it to be easily raised from the water and returned to its starting position ready for a new cycle of sweeping, all while allowing for ease of fish movement. The bench scale results with an early prototype built by WSU show that the moving baffle is able to produce average flow velocities around the baffle of 0.28-0.40 m/s which is a ten-fold increase from the average velocities in existing raceways (True et al, 2004b). This velocity increase results in an average solid transport of 3.09 g simulated waste/minute as compared to a non-baffle control of 0.04 g simulated waste/minute and a measured transport efficiency of 55% as compared to a non-baffle control of 15% (True et al, 2004b).

Weir modification

A weir modification was designed, fabricated, installed and tested at a commercial facility. The modification consisted of a series of troughs meant to distribute overflow water over a greater lengthwise distance. The modification reduced overflow velocity from 3671 ft^3/hr/m to 706 ft^3/hr/m and q-zone velocity from 0.26 ft/s to 0.16 ft/s. Particle size escaping q-zone was reduced by 11μm. However, no improvement in removal efficiency was observed.

High-rate filtration media for use in raceway applications

Two types of unique high-rate filtration media, reticulate foam media of four porosities and Fuzzy filter® (FF) media (Schreiber Technologies, Trussville, Alabama, USA), were tested to reduce solid phase phosphorus (P) discharge. Based on these results the 30 ppi reticulated foam was selected for a 16 hr field test to measure particle size capture, head loss, and the effect on solids and P discharge from commercial FT raceway effluent. The results indicated particle size capture of less than 100 μm, a cumulative head loss of 150 mm, and a 29% reduction in suspended solids and solid phase phosphorus discharge (11% total phosphorus discharge reduction) from the filtered effluent.

Objective 6. Evaluate the best management practices in commercial settings

The project work group decided based upon positive industry response, ease of implementation, and projected cost effectiveness, that the center piece of the management practice will be the moving baffle. After lab scale experiments demonstrated the effectiveness of moving and hinged baffle systems to increase particle transport rates, which thereby decreased residence times in raceways, a commercial scale test was performed. During May, 2003 experiments were performed at the UI Idaho Springs Research Farm to evaluate effects on raceway velocity profiles and solids transport. The moving and hinged baffles increased bottom velocities respectively by 1,200% and 700% above the control. The moving baffle induced a velocity of 0.12m/s, while the hinged baffle managed 0.7 m/s. Improvements in removal above the 17% of the control were also observed for both systems with 83% and 60% for moving and hinged baffles, respectively.

A small mock up baffle was built and tested in February 2004 under simulated raceway conditions at the University of Idaho's Aquaculture Research Institute. Using this information a full scale baffle was constructed and installed at the University of Idaho, Idaho Springs research farm in April 2004. Visual observation demonstrated the effectiveness of the baffle in moving fecal particles down the raceway to the quiescent zone and the ability of fish to pass.

A second generation baffle was designed incorporating several new features to address operational problems encountered with the first prototype. The baffle was tested at UI's experimental fish farm three times. Although improvements were observed, the baffle is still not functioning properly due to the increased resistance to moving after the modification. Nonetheless, the improvements have further demonstrated that the concept is feasible. A commercial company (RDM Technologies) has contacted Washington State University to license the technology for commercialization with additional refinements. Furthermore, a USDA SBIR proposal was developed as a collaborative effort between RDM and WSU for the refinement and commercialization of the baffle technology.

Outreach

One popular press article in 2 publications (Aquaculture Magazine and Waterlines) was published. Additionally, demonstration experiments were conducted dealing with phosphorus levels developed in pond and raceway culture and disposal of these phosphorus effluents on field crops. This has been recognized as a Best Management Practice in the newly released EPA Guidelines for Disposal of Aquaculture Effluents. Furthermore, the website at http://ag.arizona.edu/azaqua/extension/BMPs/Final_EPA.html was recently created to provide the new EPA Guidelines to aquaculture producers in the Western Region (and beyond). EPA determined that the most effective measure for reducing phosphorus in discharges was to limit and reduce solids, minimize release of uneaten food and dead animals and to develop and maintain a BMP plan for each farm. Considering that much of our research in this project support these exact determinations, we feel that we have been directly on the right track all along. The project will continue to develop the formal materials and assist producers to develop their individual BMPs' and institute them on their farms.

IMPACTS:

A significant amount of new information has been generated from the project. Integrating the information not only provides new insights for understanding P release and particle transport processes, but also results in new management practices and technologies that reduce P discharge from flow through raceway systems. Key results are: 1) The feed study can be used in feed manufacturing process to increase fecal stability in the raceways; 2) The P release study suggests that the fecal particle should be removed from the raceway system as soon as possible; 3) The modeling results allow for evaluation of different measures to improve flow pattern to facilitate particle transport; 4) The moving baffles provide the mechanisms to transport the particles from the raceways to the q-zone; 5) The results on q-zone size studies suggest the q-zone length required to remove certain sized particles; 6) The results of the filter study provide options to enhance the removal efficiency of the particles; 7) The moving bed reactor results demonstrate a new technology that has great potential to remove dissolved P.

RECOMMENDED FOLLOW-UP ACTIVITIES:

Further demonstration and outreach activities are recommended to maximize the benefits of the project to the industry. As mentioned previously RDM Technologies has contacted Washington State University regarding licensing and commercialization of the technology after further refinements. In order to achieve these goals a USDA SBIR proposal was developed between RDM Technologies and WSU as a collaborative effort. Additionally, due to the success of this project, continued research related to phosphorus removal in flow through aquaculture systems has been funded through the Washington-Idaho Aquaculture Initiative. It is also important to develop new technologies for the removal of particles in the effluent to supplement particle settling in the quiescent zone.

SUPPORT:

Year	WRAC Support	Other Support					Total support
		University	Industry	Other Federal	Other	Total	
2000-2001	$89,033						$89,033
2001-2002	$112,985						$112,985
2002-2003	$99,212						$99,212
2003-3004	$82,528						$82,528
2004 -2005	$31,265						$31,265
Total	$415,023						$415,023

PUBLICATIONS, MANUSCRIPTS, OR PAPERS PRESENTED

Publications

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Fitzsimmons, K., Piedrahita, R. Chen, S, and Hardy, R. Aquaculture effluent research in the Western Regional Aquaculture Center. World Aquaculture Society – Honolulu, Hawaii. March 2004. Abstracts p. 196.

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Patents

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Dissertations

McIntosh, D. 2003. - Use of inland shrimp farm effluent for crop irrigation. University of Arizona

King, C. 2004 – Integrated agriculture and aquaculture for sustainable food production. University of Arizona

SUBMITTED BY: ________________________________ ____________
Shulin Chen, Work Group Chair Date

APPROVED: ________________________________ ____________
John Colt, Technical Advisor Date

WRAC PROJECT TERMINATION REPORT

PART II: DETAIL

PROJECT TITLE: Reducing Phosphorus Discharge from High Density, Flow-through Aquaculture Facilities

PROJECT WORK PERIOD: 3/15/00 - 4/16/04

AUTHOR: Shulin Chen, Work Group Chair
Bill Johnson

PARTICIPANTS:

Shulin Chen	Washington State University	Washington
Kevin Fitzsimmons	University of Arizona	Arizona
Raul Piedrahita	University of California, Davis	California
Gregory Moller	University of Idaho	Idaho
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John Colt (Technical Advisor)	Northwest Fisheries Science Center	Washington
Gary Fornshell (Extension)	University of Idaho	Idaho
Mark Daily (Industry Advisor)	Jones Trout Farm	Idaho

REASON FOR TERMINATION: END OF FUNDING

PROJECT OBJECTIVES

The goal of this project was to reduce the discharge of all species of P from high-density, flow-through aquacultural facilities with an emphasis on investigating the fate of P and solids between the point of particle introduction into the water and the point of removal. Specific objectives include: 1) Determine the fate of particles in raceways, including transport and breakdown; 2) Investigate the rate of excretion of dissolved P from fish and the rate of release from fecal particles in raceways; 3) Design and evaluate scrap iron granule reactors for removing dissolved P; 4) Improve fecal pellet stability and minimize P loss through feed manipulation; 5) Develop best management practices featuring excretion reduction and efficient removal of both particulate and dissolved P; 6) Evaluate the best management practices in commercial settings

PRINCIPAL ACCOMPLISHMENTS

Objective 1. Determine the fate of particles in raceways, including transport and breakdown

Facility characterization

This study utilized four commercial farms and one training facility located in the Thousand Springs area of Southern Idaho, USA. The farms employed concrete raceways each consisting of a rearing area and a q-zone. The raceways were serial-reuse systems with water flowing by gravity through 4-6 raceway sections prior to discharge. All facilities were characterized in terms of raceway and quiescent zone dimensions, raceway and farm flow volume, raceway rearing volumes, fish loading densities, and annual production. Raceway flow rates were determined by using weir length/overflow height relationships based on measured water heights over the inflow weirs. Total farm flows were acquired from facility archives. Rearing volumes, fish densities, and production values were established from physical dimensions, production records, and or interviews with the farm staff.

Water velocity profiles

Raceway water velocity profiles were developed from measurements at the length-wise mid-point of the raceway, using a Marsh-Mcbirney velocity meter (Marsh-Mcbirney, Flo-mate 2000, Frederick, Maryland, USA). Measurements were taken in triplicate at three locations spaced equally across the raceway width and denoted according to their positions when facing upstream; left, middle, or right. Four vertical measurements, 2.5 cm from the bottom and at 20, 60, and 80% of the water column depth, were taken at each width-wise location.

Effluent Characterization

Farms 2 and 4 were chosen as representative of commercial trout farms in Southern Idaho. Sampling for effluent characterization was conducted in August 2001 and January 2002. Effluents were characterized in terms of total phosphorus (TP), solid (particulate) phosphorus (SP), dissolved phosphorus (DP), total suspended solids (TSS), particle settling velocity (SV), and particle size distribution (PSD). The P content of discharged solids was calculated using the TP, SP, DP, and TSS values. Phosphorus partitioning by phase and particle size was also determined.

Sample collection

Water quality samples were collected in triplicate for both farms throughout the day and were spaced generally as morning, mid-day, and afternoon. Effluent samples were taken from weir overflows of the last use raceways during normal operational conditions, i.e. no raceway cleaning and no fish grading or harvesting. Samples were collected according to the methods found below prior to being stored at 4 ± 2º C until analysis. All water quality analysis was conducted at the Water Quality and Waste Analysis Laboratory of the Biological Systems Engineering Department, Washington State University.

Total suspended solids

Total suspended solids were sampled using a sieving technique. Forty-eight to sixty L of effluent was passed through sieves with 10, 53, and 105 µm openings, respectively. Triplicate samples were collected for each sieve size. The captured material was then washed from the sieve with one liter of deionized water and funneled into 1 L sample bottles. The total suspended solids were then measured and back calculated to account for the 48-60 L concentration.

Total, solid, and dissolved phosphorus

Total phosphorus samples were collected as 1 L grab samples. SP was determined by analyzing the P content of the TSS samples. Dissolved phosphorus was determined by subtracting the SP values from the TP values. The distribution of SP per particle size was determined for particle sizes from 10 to 53 µm, 53 to 105 µm, and greater than 105 µm, by pairing the TSS values for each size class with the TP content of that material. These TP values were then divided by the corresponding TSS value; giving TP as a percentage of TSS for each size class.

Settling velocity tests were performed for larger (>814 µm) and smaller (<814 µm) particles using a top loading UFT-type settling column as described by Wong and Piedrahita (2000). Samples for large particles were siphoned from the settled material in the raceway rearing areas using a 3.5 cm diameter flexible hose. Small particles were collected by concentrating 440 L of q-zone effluent through a 10 µm filter bag.

The column was first filled with 15ºC deionized water, which was the same temperature as the raceways. According to recommendations, one to two grams of material was then placed into the upper reservoir, gently stirred to suspend the material, and introduced into the settling column at time 0 (Wong and Piedrahita, 2000). Samples were allowed to settle for 120 minutes with settled particles being collected from the settling column at 10, 30, 90, 120, 300, 3,600, and 7,200 seconds for large particles and 240, 480, 720, 960, 1,920, 3,600, 5,860, and 7,200 seconds for small particles. For each sampling time, a sample was taken by opening the stopcock at the base of the column for 3 seconds. At the end of the test the entire remaining volume was collected and recorded as the unsettled portion. The samples were analyzed for TSS, from which mass based settling curves were generated. Settling velocities were calculated based on particle travel distance and sampling time with an applied correction for changing water level in the column (Wong and Piedrahita, 2000).

Particle size distribution

Effluent PSD was determined using two different methods. The first employed data from the TSS evaluation. Assuming the TSS value from the 10µm sample to be the total settleable TSS, the 53 and 105 µm values were computed as fractions of the 10 µm value. TSS was then placed in three size classes; 10 to 53 µm, 53 to 105 µm, and greater than 105 µm providing a general size distribution.

The second method provided a continuous distribution. Forty-eight liters of effluent was concentrated over a 10 µm bag filter. Samples were then rinsed with deionized water into 1 L bottles. In order to control changes in particle size prior to analysis, all sample bottles were filled completely to prevent sloshing then immediately placed on ice until being held at 4 ± 2°C to prevent bacterial growth until analysis. Measurements were taken with a laser diffraction particle size analyzer (Malvern Instruments, Mastersizer S, Worcestershire, UK) and recorded as the volumetrically weighted particle sizes at the frequency of occurrence in the measured sample volume. Using this data, continuous and cumulative size distributions were constructed.

Results

Facility characterization and flow rates

The raceway dimensions ranged from 0.6-0.9 m in water depth, 2.1-5.5 m in width, and

12.1-48.8 m in length. Q-zones measured 3-6.5 m in length and had the same width and depth as the raceways. Farm flow rates ranged from 5,400-510,000 L/min, with individual raceway flows of 946-10,200 L/min. During sampling, raceways contained rainbow trout approximately 35 cm in length and weighing 500-800 grams per fish. Total fish biomass was approximately 1,700 kg and 7,000 kg in the sampled raceway sections at Farm 2 and 4, respectively. The data collected is presented in Table 1.

Raceway velocities

An ANOVA was performed on water velocities for all farms using the general linear model in SAS (SAS Institute, Cary, N.C.). Mean water velocities at 20, 60, and 80% of the water column depth and 2.54 cm from the bottom were 0.057 ± 0.0035, 0.050 ± 0.0037, 0.049 ± 0.0035, and 0.021 ± 0.0040 m/s respectively. The mean velocity at the bottom of the raceways was found by least square means comparison to be significantly lower than the other sampling points ($P<0.0001$). Raceway water velocity profiles for Farms 2 and 4 are shown in Figure 1.

Effluent Phosphorus characteristics

Mean P concentration in particles greater than 10 µm were found to be 0.04±0.02 mg/L and accounted for 3.40±1.08 % of the TSS (Table 2). An analysis of variance (SAS Institute, Cary, N.C.) indicated no significant statistical difference ($P>0.11$) per size class. Overall mean TP, SP, and DP discharge were 0.09±0.01 mg/L, 0.04±0.01 mg/L, and 0.06±0.01 mg/L, respectively. The DP represented the majority of the discharge (62%), while SP represented the remainder (38%).

Settling Velocities

The results of average settling velocity tests for large and small particles are shown in Figure 2. The average settling velocities were 2.31± 0.00 and 0.16±0.00 cm/s (0.0231 and 0.0016 m/s) for large and small particles, respectively.

Total Suspended Solids and Particle Size Distributions

Total suspended solids values for each size class are shown in Table 2. The mean concentrations of TSS for particles greater than 10, 53, and 105 µm were found to be 1.93±0.81 mg/L, 1.34±0.64 mg/L, and 1.01± 0.68 mg/L, respectively. Therefore, of the discharged mass greater than 10µm 69% was greater than 53µm and 52% was greater than 105 µm,

The particle size distribution data obtained with the Mastersizer are shown in Figures 3 and 4. The median volumetrically weighted discharged particle size was 250.1± 8.8 µm. The particle sizes for the 10th, 50th, and 90th percentiles were 57.0±6.7, 213.5±10.5, and 500.1±20.4 µm, respectively. The largest particles measured were 814µm with an occurrence frequency of 0.6% at both sites while the smallest with measured occurrence frequencies of 0.1% were 2 and 1.5 µm for Farms 2 and 4, respectively (Figure 3 and 4). In comparison with the sieve analysis these distributions indicate that 89% and 76% of the particles were greater than 53 and 105 µm.

Computational fluid dynamics modeling of raceways

A computational fluid dynamics (CFD) model of flow in a raceway was developed and the model was used to analyze potential QZ modifications and their impact on solids accumulation within the QZ (Huggins, 2003). The concrete raceway used in this study was 30.18 m long and 3.05 m wide, with a maximum depth was 0.91 m and a slope of 0.01. The rearing volume, not including the quiescent zone (QZ=5.07m), was approximately 48.4 m^3. Each of the inlet and outlet flows were through two weirs that together add to the total width of the raceway (Figure 5). The fish stocking density was 11 kg/m^3 with an average mass of 49 g per fish. The sides of the raceways are defined as inlet wall (IW), outlet wall (OW), right hand side (RHS), and left hand side (LHS), respectively for description and measurement purposes (Figure 5). The flow rate was calculated using the Francis equations for half-contracted rectangular sharp weirs (Vennard, 1954) as 3,486 L/min (0.058 m^3/s).

The model was created using the software package Sediment Simulation In Intakes with Multiblock option (SSIIM). The model was used to study the potential impact of QZ modifications on the efficiency of sedimentation within the QZ of six groups of particles with mean settling velocities of 0.01 to 3.9 cm/s, corresponding to sizes of 35 to about 700 μm, respectively (Table 3. Diameters estimated with Stokes' Law assuming a density of 1150 kg/m^3; Metcalf &Eddy, 1991;Wong, 2001; Timmons et al., 2002). This efficiency was estimated as the percentage of solids removed (PSR), which corresponds to the fraction of the solids introduced into the raceway (TSI) that settle in it assume non-cohesive sediment particles and ignoring re-suspension.

Model characteristics

The selection of SSIIM for this study was based primarily on its capability to simulate sediment movement. SSIIM is a freeware computational fluid dynamics (CFD) program that can be downloaded from the internet (Olsen, 2002). In addition, SSIIM supports multiple operating system platforms and can be executed in computers running under any version of Windows^{TM}. The program is relatively small (1.3 MB) and is not very resource intensive.

The water flow calculations are based on the Navier-Stokes equations for turbulent flow in a general 3D geometry for non-compressible and constant density flow (Olsen, 1991). As in any model, a number of assumptions had to be made. The main assumption was that the effect of fish swimming in the raceway was not considered, and this gave rise to a number of specific assumptions in the model. Given the potential impact of fish swimming on water flow in general and on sediment transport in particular, a result of this assumption was that model validation and model use were concentrated on the QZ, an area from which fish are normally excluded. Given the emphasis on the QZ, the raceway influent was assumed to be uniformly distributed through the upstream end of the raceway. Another outcome of neglecting the impact of fish was that the location of sediment introduction into the raceway was selected to be the surface just upstream of the QZ. Normally, sediments settle throughout the full length of a raceway but they are re-suspended due to fish activity and tend to stay close to the bottom until they eventually make it into the QZ, where they settle unaffected by the fish. Conservative estimates of settling in the QZ and some settling prior to the QZ are expected due to the assumption that solids enter the raceway at the surface just upstream of the QZ. As indicated above, the model assumes non-cohesive sediments and ignores re-suspension. The assumption of non-cohesive sediments is necessary given the limitations in the capabilities of SSIIM and the limited information available on the physical and transport properties of aquaculture sediments. This assumption is likely to result in an under-estimation of PSR. A related assumption was to ignore re-suspension. This assumption had to be made due to difficulties in interpreting some of the simulation results and in accessing the code used by the developer of SSIIM. This assumption is likely to result in an over-estimation of PSR.

A screen separates the rearing area from the quiescent zone. In the real system the screen is placed at 25.11 m from the inlet wall (Figure 5) and in the simulated system the screen was placed at 25.25 m from the inlet wall. The screen in the real raceway consisted of two wood framed sections (2”x4”, nominal size). Each frame had 50 PVC pipes with an outside diameter (OD) of 2.5 cm (3/4 in nominal size), placed vertically along the whole height of the screen leaving a space of 1.2 cm between the pipes (Figure 6). The total number of closed spaces was 100 (pipes) with a total of 98 open spaces (because the first and the last pipe in each of the two wood frames were very close to the frame). This screen configuration was difficult to incorporate in the simulation due to the large number of cells that would have been required and the corresponding number of calculations needed. Therefore, the pipes were replaced with 12 bars (closed space, Figure 6) to simplify the water flow calculations. The open spaces (between pipes) in the original system add up to 19.7 % of the total width. However, the simulated open area was 22.5 % of the total width, again due to grid size limitations.

The grid used for the simulation was 70x50x16 (56,000 cells). The first number (70) corresponds to the number of grids along the length of the raceway (X axis, cross sections), the second number (50) corresponds to the number of grids along the width of the raceway (Y axis, longitudinal areas), and the third number (12) corresponds to the number of grids along the depth of the raceway (Z axis, levels). The cells are the locations at which the flow equations are solved.

Sediment transport

Sediment transport simulations were carried out using SSIIM routines. The overall TSI used for the simulations was determined by assuming that 25 % of the feed given results in suspended solids (TSS) released to the water (Timmons, et al., 2002). The TSI for each particle size group (TSI_i) was calculated from the settling velocity distribution obtained from Wong and Piedrahita’s (2000) study and the overall TSI

$$TSI_i = \text{Mass Fraction}_i * TSI \quad (1)$$

where

Mass Fraction_i = fraction of the solids that have a particular settling velocity (Table 3)

The rate of solids exiting the raceway (RSE) was calculated as the flux of sediments carried in the water flowing through the effluent weirs. Similarly, the rate of solids settled (RSA) was calculated as the flux of particles settling from the lowest horizontal grid in the raceway model (Level 2 in Z direction according to the conventions used in SSIIM). An estimate of the settling effectiveness for a particular particle group was obtained as the percentage of solids removed (PSR):

$$PSR = 100\ \%\ RSA/TSI \qquad (2)$$

An estimate of the percentage of solids not removed (PSNR) was obtained from:

$$PSNR = 100\ \% - PSR \qquad (3)$$

Sediment transport simulation results

The overall simulated RSE and RSA for all particles groups in the original system were 2,485 g/d and 11,146 g/d, respectively, resulting in an overall PSR of 81.8% (Table 3). For the original raceway configuration, the PSR for particle Groups 1, 2, and 3 was approximately 100%. For the smaller particles, the PSR was lower, 54.7%, 0.9%, and 0.1% for particle size Groups 4, 5, and 6, respectively (Table 3).

In addition to obtaining the PSR results, an analysis of the sediment flux contours was conducted to identify the areas where most of the solids tend to settle (Figure 7). The settling space characteristics are similar for particles Groups 1, 2, and 3, where the particles settle very close to the point of release due to their high settling velocity and relatively low horizontal water velocities. In particular, a large fraction of the Group 1 sediments settled before the QZ but Groups 2 and 3 showed more incursion into the QZ due to their lower settling velocities relative to that of Group 1.

Some differences in the sediment deposition of Groups 4 through 6 were observed when compared with Groups 1 through 3. The lighter particles are displaced towards the end of the QZ and the sediment fluxes for Group 4 through 6 are much lower than for the previous groups, resulting in much lower PSR values.

Raceway modifications

After analyzing the velocity profiles and sediment fluxes obtained from the model of the standard raceway and considering various design constraints, several raceway design alternatives were simulated. Among the design alternatives tested, six designs were chosen for further analysis based on their PSR values (Figure 8). The main feature in all the modifications presented is the addition of a baffle before the QZ or at the entrance of the QZ replacing the screen. The main purpose of adding these baffles was to improve the settling of solids in the QZ. The highest simulated PSR was obtained with the combination of a baffle and a screen under the baffle (Table 4). The improvement of PSR with respect to the original system was especially noticeable for the smaller groups of particles (4, 5, and 6), which corresponds to 204μm, 61μm, and 35μm in diameter, respectively.

The overall increase in solids settling in the raceway was minor, with overall PSR increasing from 81.8 % for the unmodified raceway to 91.1 % for Alternative 5, the alternative showing the best performance. Although this is a minor change in the PSR, it translates to an estimated reduction in the solids exiting the raceway of over 1,200 g/d for each raceway as the one analyzed here. This corresponds to a reduction in solids in the effluent of over 2 % of the amount of feed applied to a raceway.

The simulation results show quantitatively the effect of particle settling velocity on sedimentation effectiveness, with small differences in settling velocity causing large changes in PSR values. The simulation results presented here are specific for the settling velocity distribution used. Substantial improvements in PSR values can be expected if the settling velocity distribution of particles present in the raceway can be modified through improvements in the feed and feeding practices to produce particles with higher settling velocities.

Q-zone: sizing and cleaning frequency

The evaluation of q-zone sizing on solids and P removal was conducted by combining experimental particle size distribution (PSD), total phosphorus (TP) and total suspended solids (TSS) data with a numerical analysis using Stoke's law for discrete particle settling. Farms 2 – 5 were analyzed. The collection of the PSD and TSS samples was undertaken during the March and August 2003 field trip to study farms 4 and 2, 3, and 5 respectively.

The funnel and siphon system (Figure 9) was set up at the q-zone influent of three different raceways. The first raceway tested used the current size q-zone, the second was changed to 1.5 times the original, and the q-zone of the third raceway was changed to .5 times the original at farm 2 and 2 times the original at farm 3. The q-zones were vacuumed clean before the beginning of the test and PSD, TP and TSS samples were then collected for the influent and effluent of each setup at the beginning, middle and end of the 24 hour test period.

To determine the effect of q-zone size on discharge an analysis was begun by calculating the overflow rates of each farms quiescent zone with lengths from 1 to 12m long, representing changes of approximately 15 to 200% the current size. This was accomplished based on raceway geometry and flow rates. Then using the particle size distributions determined from the MasterSizer Laser Diffraction Particle Size Analyzer (Malvern Instruments, U.K.), and the TP, and TSS determined according to standard methods protocol for TSS analysis, it was possible to relate the TSS discharge with the PSD for a given q-zone size. To determine the effect of q-zone size on P discharge a Stoke's diameter was calculated for each q-zone length 1 to 12m and for that diameter a corresponding percentile was read from the cumulative PSD. This percent was then multiplied by the original discharged TSS and added or subtracted from the original discharge to obtain an estimated new TSS discharge corresponding to that q-zone size. Then based on previous data which determined percent P in effluent TSS the P discharge was calculated and compared to the original. The results were then graphed to illustrate changes in P discharge as a function of quiescent zone size.

The particle size distributions shown in figure10 are for raceway effluent from the last use raceway at the indicated facility. This information was then used to calculate median effluent particle sizes for the current q-zone configurations. New median effluent particle sizes where then calculated for q-zones from 1 to 12 m based on the effect on overflow rates and the solution to stoke's equation. To relate these new discharge sizes to theoretical TSS discharge the differences in cumulative frequencies between the two sizes were calculated and used to extrapolate to the new TSS values. The percent P observed in the TSS at each site was multiplied by this TSS value to get discharged P, and this value then related to measurements for the current q-zone estimate changes in P discharge. The results for this series of calculations and the PSD's used for each site are displayed in Table 5 and Figure 10 respectively.

Figures 11, 12 and 13 graphically display these results for farm 2, the other sites follow similar trends. In order to interpret the information an understanding of the nature of total discharged solid mass as related to the particle size distribution is helpful. The largest particles obviously contain the most mass and this explains the decrease in the slope observed in each of the above graphs. As one moves from a q-zone 1m in length to the current length at site 2 of 5.3m, a sharp slope is observed in all graphs, because each incremental change in the q-zone overflow rate brought on by this lengthening decreases the average captured particle size from approximately 680 to 280 µm (Figure 11). This range corresponds to largest, most easy settled particles in the distribution as well as those containing the most mass. And, this effect ripples through the remaining graphs affecting TSS discharges from 2.2 to 1.7 mg/l (Figure 12) and changes in P discharge an increase of 36% (Figure 13), at a q-zone length of 1m down to no change at the current length, 5.3m. However this effect does not remain linear as the q-zone is lengthened, because reductions in captured particle size are now in the relatively smaller size portions of the distribution, less than 280 µm. Substantially higher numbers of these harder to capture particles must be intercepted to equal the mass of a few larger particles so the "rate of return" is decreased in capturing this material by means of settling. This is clearly illustrated in Figure 13, whereas an increase in the q-zone size from a hypothetical 1m to the current 5.3m decreases P discharge by 36% the same increase once again to 10.6m reduces discharge by 12% (indicated by the negative value). This analysis has provided some important insights. At this facility to capture the target 100 µm particle more than the entire raceway length (approximately 24m) would have to be converted into a raceway.

Evaluate Q-Zone Cleaning Frequency

Because of the dilute nature of effluent at these facilities it is often difficult to observe significant changes in water quality measurements. This necessitates a well thought out procedure to evaluate the effect of q-zone cleaning frequency. A procedure was developed and then tested in the field; however, no samples were taken at this point. The purpose of the exercise was to evaluate the method, improve/modify if necessary and perfect for use during the BMP implementation at the UI Idaho Springs Research Farm.

In this method the bottom of the quiescent zone will be delineated into at least three regions, one third the total q-zone length each. The regions will be representative of various solids accumulation areas with the q-zone. For example the front of the q-zone usually initially holds a higher percentage of deposited solids than the other regions. The areas will be marked off along the bottom and sides of the raceway with survey paint or other such marker for clarity. Just prior to the beginning of the test the q-zones will be vacuumed clean. A solids deposition rate will then be established by siphoning clean a known area of each region. This will be accomplished by lowering a clear acrylic open-ended box of known area onto the raceway bottom. The solids contained with the box will then be siphoned off into a 10 μm filter bag. The wet solids will be weighed and the results will be a solids deposition flux (solids per bottom area) for that region. In the field test a 5/8” siphon hose was attached to a handle operated by one person and a hand pump was operated by another to begin the siphon. The same person also collected the siphoned solids. Then knowing the deposition rate, total q-zone area, solids production and using the short and long term P dissolution rates determined the amount of dissolved P will be estimated. The procedure was performed during the August 2003 field trip, at study site 4 in Southern Idaho, and was able to effectively collect deposited solids over a known area.

Q-zone phosphorus release model

In order to determine the optimal cleaning frequency of the q-zone, a high priority has been placed on the development of a P release model for the q-zone. The model developed is specific to P exchange at the sediment-water interface. The aim is to simulate the sink and supply of P in the q-zone. This will be accomplished by:

1) Performing laboratory and field experiments to understand P movement in q-zone
2) Develop mass balance P transfer model that includes P fate and routing routines
3) Validating the model with data collected from field

The model was developed assuming steady state conditions. Process formulations were found in the literature.

We usually think of phosphorus more in terms of total phosphorus (TP) in raceway systems, though P actually occurs in aquaculture systems in four different forms (Fig. 14): dissolved inorganic phosphorus (DIP), particulate inorganic phosphorus (PIP), dissolved organic phosphorus (DOP) and particulate organic phosphorus (POP). The inorganic forms are phosphates and the organic forms are molecules derived from the decomposition of biochemicals. There are important interconversions between the different forms. The diagram illustrates each of the four major types of phosphorus, the major sources for each type, the interconversions between them and the possible fate of each form. For simplicity, biological uptake of phosphorus is not included in the diagram. DIP is biologically available and essential to plants and algae and is mostly dissolved phosphates that enter the raceway from source water and through the gills and kidneys of fish and is removed from the raceway by water exchange. It is produced in the raceway from organic P by bacterial and algal phosphatase activity and converted to PIP by sorption and precipitation.

PIP is mostly not biologically available and is phosphate associated with phosphate minerals and adsorbed on metal hydroxides and other solids in the raceway. It enters the raceway mostly in fish food and feces and can be removed by siphoning out sediment. It is formed within a raceway by sorption and precipitation of DIP which is biologically available to bacteria and possibly to algae. It enters the raceway from fish waste and can be removed by water changes. Bacterial and algal phosphatase activity convert DOP to phosphates. POP is not available to plants and algae, but is available to animals. It enters the water as fish food and feces. It can be removed by siphoning and solids re-suspension and is converted to dissolved phosphates by phosphatase activity.

In this study, we were concerned about reducing TP discharge through optimal cleaning frequency of the quiescent-zone. Only Dissolved P (DP) and particulate P (PP) were considered in this research.

The P cycle was described as follows (Fig. 15):

In aerobic layer of sediment: Dissolved P released by degradation (aerobic) enters pore water, and dissolved P diffuses to over layer water by the force of concentration differences. Dissolved P in pore water is absorbed by Fe3+ and Mn2+ into particles and covered by fresh sediment (settling to anaerobic layer).

In sediment: Dissolved P is released from particles under anaerobic condition and dissolved P diffuses up (to aerobic layer) by the force of concentration difference. Because particles continue settling down, a fixed thickness in aerobic layer and a fluctuating thickness of anoxic layer is produced.

To model the P dynamics in sediment that is based on a two layers assumption, we have developed a mass balance box model (Fig. 16).

Kinetics of sedimentary processes
Aerobic layer
TP Mass balance (Fig. 17):
Sdif-w = (Sset – Smix) + Sad-w + Sdif-s

The diffusive flux between sediment and water

$$S = -\varphi \frac{D_0}{1.28\varphi_0^3} \frac{\Delta C_{s-w}}{\Delta z}$$

Where C=concentration of DP, umol/m^3; ΔCs-w=difference of DP concentration between the water near the sediment surface and the porewater, umol/m^3; Δz=depth of the sediment layer, m; φ=porosity, cm^3/cm^3; φ_0=average porosity between the layer studied and the layer above, $\varphi_0=(1+\varphi)/2$; D_0=phosphorus-free solution molecular diffusivity; $D_0 = (0.086T+1.8)\times10^{-6}$, m^2/h.

The degradation of organic P
$S_{mix}=S_{set}\ 10^{-1/T90}$
Where T_{90} is the time required to degrade 90% of the biodegradable P in a given environment. The estimated decay rate of P was 0.005/day at 14^{o}C and 0.013/day at 20^{o}C.
The diffusive flux between layers

S_{dif}=Ds × A/z × ΔC_d × φ
Where Ds=sediment diffusion coefficient m^2/day; z=distance between the centers of the two layers; A=exchange area.

Adsorption and desorption
$S_{ad} = k_a \times (1- S_{ad\text{-}s}/ S_{ad\text{-}max}) \times S_d$
$S_{de} = k_d \times S_{ad\text{-}s}/ S_{ad\text{-}max}$
Where k_a=adsorption rate (/day), k_d =desorption rate (mmol/m^3day);
$S_{ad\text{-}s}$=DP have been adsorbed; $S_{ad\text{-}max}$=maximal adsorption capacity of sediment (ug/g);
S_d =dissolved P in water or pore water.
In the model, the sediment becomes anoxic when oxygen drops bellows 0.2mg/l.

Anaerobic layer
TP Mass balance (Fig. 18):
TP=Smix – Sdif-s

Adsorption and desorption
Sad = ka' × (1- Sad-s / Sad-max)× Sd
Sde = kd' × Sad-s / Sad-max
The ratio ka'/kd' decreases in anoxic conditions from 3 to 11 times.

Sediment oxygen consumption
Oxygen consumption by mineralization and nitrification need be considered.
So=ρ g (Sset-Smix)/(Sset × p)
Where ρ = oxygen consume rate of degradation, mg/g organic matter; g= % of organic matter in sediment; p=% of P in sediment.

Sediment oxygen diffusion
Sdif-o=Dso × A/z × ΔCo × φ
Where Dso=diffusion coefficient for oxygen in sediment (m2/s).

Optimal q-zone cleaning frequency
For T=1 to n days, in one year, total P discharge:
Sp=[ST+ Sc(T)] × 365/T
Tp=Tmin(Sp)

Where Sp = total P discharge; Sc=TP released by q-zone cleaning operation; Tp=optimal cleaning frequency, days/cleaning; ST = total P release from sediment with cleaning frequency T days/cleaning.

Some field studies have been completed and show that:

1. Cleaning q-zones was helpful to reduce TP discharge (about 12.5%), but TP discharge level is restored very soon (about 90 minutes) after cleaning.
2. During 24-119 hours after q-zone cleaning, TP discharge from q-zone did not increase significantly.

Combined with the analysis of the mass balance box model, we believe that before the anaerobic layer exists TP release from the sediment will not increase significantly because of the strong absorption of $Fe^{3+}$and Mn^{2+} particles. Under the labor cost concern, the optimal cleaning frequency of q-zone may depend on both the moment when the sediment turns to anoxic and the amount of TP discharge during the cleaning operation.

A fully distributed modeling of TP release from sediment requires the data of the actual degradation rate of organic P, dissolved P diffusion rate between two layers, dissolved P concentration in pore water and oxygen distribution in sediment. Unfortunately, such data is not available. Therefore, further field studies need to be performed for validation of the model.

Objective 2. Investigate the rate of excretion of dissolved P from fish and the rate of release from fecal particles in raceways

The basic problem with tracing particles of solids and the phosphorus leaching from them on an operating farm is that we are only able to determine the background level of phosphorus and not discrete molecules of phosphorus in feed, feces, and fish. Tracking labeled phosphorus would be the logical solution. But phosphorus isotopes are not stable, so we decided to experiment with other molecules that could be used as markers.

We examined the levels of naturally occurring carbon and nitrogen isotopes in water, feed and fish from Jones Trout Farm in Idaho. We determined that these isotopes could be used as surrogates for tracing phosphorus in the system, as the natural isotopes of phosphorus are very short-lived and unstable. They are also prohibitively expensive to purchase and analyze. The first year's results demonstrated that nitrogen isotopes had the better correlation to the actual phosphorus levels that we sampled in the water, feed and fish.

Therefore, a diet was prepared that contained an elevated level of 15N that could be traced through the system. Ammonium-nitrate (15N nitrate-98%) was mixed with cod liver oil and applied to feed already being used at a commercial farm. The demand feeders were refilled with the labeled feed. Fish were allowed to feed normally while water samples were collected every two hours for the next 48 hours.

Water analyses for pH, phosphorus, dissolved oxygen, and temperature were determined at the farm, or at the University of Idaho lab in Hagerman. Feed, feces and fish were collected and brought back to an isotope lab at the University of Arizona. Water samples for isotopic analyses were sent to a lab on the main campus of University of Idaho.

Materials and Methods

Day 1 (May 14)
    Spray 50 lbs. of feed with oil/isotope mixture
    Prepare 500 ml of 1.0 N H_2SO_4
    Prepare 500 ml of 1.0 N NaOH
Day 2 (May 15)
    Collect initial water and fecal samples *
    Feed fish in Raceway 6, Section 1 with isotope spiked feed to satiation

Refill demand feeder with regular feed
Begin 48 hr. sampling *
Day 3 (May 16)
Continue 48 hr. sampling
Day 4 (May 17)
Finish 48 hr. sampling
Day 5 (May 18)
Return to Tucson w/ whole fish & fecal samples

Water samples were frozen and left at the University of Idaho lab. Brit Johnson, one of Shulin's grad students, picked up samples and delivered to the water quality lab at the Moscow campus where they were analyzed for the isotopic signatures.

* Sampling Notes

Water Sampling (T = 0 hr. - 48 hr.)
- Isotopic Analysis
  - every 2 hrs. (3 L / sampling)
  - samples to be frozen & stored at UI lab
- Total Phosphorus
  - every 2 hrs. (3 replicates / sampling)
  - samples collected & analyzed on site
- Dissolved Oxygen
  - every 2 hrs.
- pH
  - every 2 hrs.

Solid Samples (T = 0 hr. - 48 hr.)
- Feed
  - collect 1 sample of regular feed (~4 oz.)
  - collect 1 sample of spiked feed (~4 oz.)
- Fish
  - T = 0, 12, 24, 36, 48
  - collect 3 - 4 fish (~2 oz. dry)
  - composite sample
- Feces
  - every 1 hr.
  - composite sample from 2 collectors

P dissolution rate from feces

Samples of feed, whole fish, fish feces and water were collected from a commercial trout farm in Hagerman, Idaho in July 2001. Sample collection began at 09:00 on July 6th and continued at 3-hour intervals for 12 hours. At each sample time, effluent water from one trout production raceway was collected from the quiescent zone, along with a sample of fish feces. In addition, at 09:00, samples of feed from the demand feeder, raw spring water, spring pump-back water and raceway influent water were also collected. Whole fish were sampled at 15:00 and 18:00.

At each sampling time, duplicate water samples were collected, one for total P analysis and one for ^{13}C and ^{15}N analysis. Water for total P analysis was collected with a 400-ml beaker and transferred to a polyethylene bottle containing sulfuric acid as a preservative. Samples for isotopic analysis were collected directly in 1-L polyethylene bottles. No preservatives were used for these samples. Solid samples, with the exception of whole fish, were collected in 250-ml wide mouth polyethylene bottles. Fish were randomly collected with a dip-net and placed into whirl packs. Solid samples were not preserved prior to freezing.

All water and solid samples were frozen at the University of Idaho's Hagerman Fish Culture Experiment Station and transported to Arizona for analysis. Upon arrival in Arizona, solid samples were dried in an oven at 104°C. After drying, solid samples were ground using a mortal and pestle to facilitate P and isotopic analysis. Total P samples were analyzed by a commercial lab (Turner Laboratories Inc., Tucson, AZ). Isotopes of ^{13}C and ^{15}N in solid samples were analyzed by the Department of Geoscience at the University of Arizona.

Following sample collection and analysis, data was analyzed to expose the relationship between total P and ^{13}C and/or ^{15}N. The computer software package, JMP IN v4 (SAS Institute Inc., Pacific Grove, California) was used to test the linear regression of P on $\delta^{13}C$ and $\delta^{15}N$. Using data from the literature concerning phosphorus retention in trout, a correction factor was developed to help explain the relationship between P and isotopes of C and N.

Results:

Water Samples

Total P concentrations at the spring source (raw spring water), spring pump-back water and water entering the raceway were 0.01 mg/L. Effluent water P concentration averaged 0.03 mg/L, ranging from 0.01 to 0.06 mg/L.

Solid Samples

Note: Isotopic ratios are reported as % higher of lower than standard ratio. Thus (-21) means that the $^{13}C/^{14}C$ ratio is 21 % lower than normal. This signifies that some partitioning has taken place. Feed collected from demand feeder was 0.62% P, by weight. Whole fish were 0.75% P by weight. Percent P in fish feces was between 1.6 and 1.9%, with an average of 1.7% (Fig. 19). Carbon 13 ratios differed only slightly among samples of feed, whole fish and feces ($p = 0.0511$, $F = 5.7173$, df = 7). The ^{13}C ratios of feed (-21.88) and whole fish (-21.29) where similar ($p = 0.4544$, $t = 0.8107$). Mean $\delta^{13}C$ in fish feces was -22.92, higher than either feed ($p = 0.174$, $t = 1.584$), or whole fish ($p = 0.0224$, $t = 3.261$). Nitrogen 15 isotope ratios were not as similar between feed, whole fish and fish feces as were carbon isotopes ($p = 0.0010$, $F = 37.0771$, df = 7). Feed $\delta^{15}N$ was 7.99. Mean $\delta^{15}N$ of whole fish was higher than the feed, at 11.23 ($p = 0.01$, $t = 4.03$), while mean $\delta^{15}N$ of fish feces was lower than the feed, at 6.50 ($p = 0.0933$, $t = 2.07$). The difference in $\delta^{15}N$ between whole fish and feces was

4.721 ($p = 0.0003$, $t = 8.609$).

Numerous simple linear regression models of $\delta^{13}C$ and $\delta^{15}N$ on the %P were fit. Figures 20 and 21 are the original regression models of $\delta^{13}C$ and $\delta^{15}N$ on %P, respectively. Looking at the R^2 values for both, we see that the regression of $\delta^{13}C$ on %P accounts for only 48.5% of the variation and the regression of $\delta^{15}N$ on %P accounts for 63.6% of the variation. While explaining 64% of the variation might be sufficient for some things, we felt that a better explanation of the variation was necessary.

In order to better explain the relationship P and isotopes of C and N, a correction factor was developed. It has been reported that 46% of the dietary P is retained in the fish, 46% is excreted in the feces and the remaining 8% is excreted into the water from the gills and as urine (Hardy 1999). Using these figures, the %P found in the samples was adjusted as follows: %P in feed were multiplied by 1 and %P in both fish and feces were multiplied by 0.46, corresponding to the expected percentage of P retained in each.

With the corrected %P values, the linear regressions of $\delta^{13}C$ and $\delta^{15}N$ were re-run (Figs. 22 and 23, respectively). The linear regression of $\delta^{13}C$ on %P (corrected) explains about as much variation as the previous model, 48.4% versus 48.5% from the regression of $\delta^{13}C$ on %P. Despite negligible effects on the linear regression of $\delta^{13}C$ on %P, correcting %P as described above made a substantial difference in relation to $\delta^{15}N$. Our initial regression of $\delta^{15}N$ on %P explained 63.6% of the variation on the model. Using the corrected values of P enables the regression of $\delta^{15}N$ on %P to explain 86.2% of the variation.

Implications:

The model we developed has certain limitations, primarily the small sample size. As the remaining data are collected, namely the $\delta^{13}C$ and $\delta^{15}N$ in the water samples, we believe the model become more robust. Overall, however, we are pleased with amount of variation in %P that can be explained by $\delta^{15}N$ after correcting for the expected P retention in the fish and feces (86.2%). We had hoped that the ratio of naturally occurring isotopes in the feed would allow us to track P. However, this is not possible in a system that has existing populations of fish, which already are on feed. These data suggest that using $\delta^{15}N$ as a proxy for P will allow us to much more accurately determine the particle residence time in a high-density, flow-through aquacultural facility, through the use of ^{15}N enriched amino acids incorporated into a test diet.

Biological breakdown

Determination of the Leaching Rate of Total P (TP) & Reactive P (RP) From Trout Feces Through a Series of Laboratory Experiments

Materials and Methods

System Description

A series of leaching trials were conducted between March and December 2002 to determine what effect water velocity and water temperature have on phosphorus leaching from trout feces. A hatchery-reared population of rainbow trout (*Oncorhynchus mykiss*) was held in a 3,300-L semi-closed recirculating system at the University of Arizona's Environmental Research Lab in Tucson, AZ for use in these trials. The culture system consisted of a 2,255-L raceway with mechanical and biological filtration. Water circulation was provided by a 1.0 hp centrifugal pump and water temperature was maintained in the culture system through the use of a 1.5 hp inline chiller (Model AFC-8, Aquanetics Systems, Inc., San Diego, CA USA).

Fresh water was added to the system at a rate of 1,440 L/day (44% exchange/day) and raceway water quality was checked periodically to ensure that adequate culture conditions were being maintained. Fish in the captive population were fed a 5.6 mm (7/32") floating commercial trout diet (Starr Milling, Perris, CA) to satiation twice daily at 7:00 and 14:00 Monday through Friday and once daily at 11:00 on Saturday and Sunday. Feed details are summarized in Table 6.

Leaching Trials

Leaching trials examined three water velocities and two temperatures in a 3 x 2 factorial design. Experimental water velocities corresponded to a settling basin (0.027 m/s), normal raceway flow (0.079 m/s) and raceway flushing (0.134 m/s). Water velocity was created in the experimental containers using a paddle mixer (Model 7790-400, Phipps and Bird, Inc., Richmond, VA USA) set at 5, 15 or 25 RPM to obtain the desired velocity of 0.027 m/s, 0.079 m/s and 0.134 m/s, respectively.

Two experimental temperatures, low (14.0 ± 0.36 °C) and high (19.3 ± 1.05 °C), were chosen to bracket the common range of water temperatures observed on commercial trout farms in the western United States. Culture water temperature was manipulated for each trial to ensure that temperature effects being investigated did not exclude any effects of temperature on dietary phosphorus uptake. Therefore, temperature was maintained in the experimental containers during the leaching trials by suspending them in the filter portion of the recirculating culture system in a specially designed apparatus.

For all trials, six fish were randomly collected from the captive population one hour after the morning feeding and anesthetized with tricane methane sulphonate (MS222). Feces was then manually stripped from each of the six fish, with individual samples being added to separate 1-L beakers of de-ionized water maintained at ambient raceway temperature. Following feces collection, fish were returned to the captive population.

The water/feces mixtures were stirred continuously with the paddle mixer for four hours. During this time, sub-samples of water were analyzed for total and reactive phosphorus every 15 minutes for the first hour and every 30 minutes for the remaining three hours. Following the four-hour leaching trials, feces was collected on a pre-weighed, 0.45 μm glass-fiber filter. Concentrated fecal samples were oven dried at 104 °C to a constant weight to ascertain the dry weight of feces stripped from each of the six randomly selected fish.

Data Analysis

Phosphorus loads in the experimental containers were calculated by multiplying the total and reactive phosphorus concentrations measured during the four-hour leaching trials by the volume of water remaining when each sub-sample was taken. Scatter plots of the phosphorus load in the experimental containers over time were created for each fish/fecal sample and regression analysis was used to determined phosphorus leaching rate. Leaching rates were normalized by dividing individual leaching rates by the dry weight of feces stripped from the respective fish.

Data were analyzed using the statistical software package JMPin v 4.03 (SAS Institute Inc., Cary, NC). A two-way ANOVA ($\alpha = 0.05$) was used to test for leaching rate differences as effected by water velocity and temperature.

Results:

Raceway Water Quality and Flow

Between March and December 2002, water quality in the culture system stayed within the acceptable limits for rainbow trout culture (Table 7). Temperature ranged from 13 to 21 °C and dissolved oxygen stayed above 5.25 mg/L throughout the experiment. Mean pH was 7.34 ± 0.134 and alkalinity averaged 140 ± 4.6 mg/L as $CaCO_3$. Mean ammonia-nitrogen was 0.14 ± 0.040 mg/L, mean nitrite-nitrogen was 0.14 ± 0.053 mg/L and mean nitrate-nitrogen was 4.7 ± 0.59 mg/L. Freshwater flow into the system averaged 1.01 ± 0.098 L/minute.

Reactive Phosphorus Leaching Rates

There is no evidence to suggest that reactive phosphorus leaching rates are affected by water velocity ($F_{2,52} = 0.7534$, $p = 0.4758$, from a two-way AVOVA) (Table 8a). Temperature, however, does appear to affect the leaching rate of reactive phosphorus from trout feces ($F_{1,52} = 4.6445$, $p = 0.0358$, from a two-way AVONA), with reactive phosphorus leaching from feces 1.92 mg PO_4/hr/g feces faster at a higher temperature (Table 8b). Mean reactive phosphorus leaching rates were 2.88 ± 0.704 and 0.96 ± 0.581mg PO_4/hr/g feces, for the high and low temperatures, respectively. Despite the significant difference in leaching rates as a result of temperature, the effects of temperature and water velocity are independent ($F_{2,52} = 0.3662$, $p = 0.6951$, from a two-way ANOVA).

Total Phosphorus Leaching Rates

Total phosphorus leaching rates (Table 8a and 8b) do not appear to be affected by either water velocity or temperature ($F_{2,52} = 1.2445$, $p = 0.2965$ and $F_{1,52} = 0.0869$, $p = 0.7693$, respectively from a two-way AVONA). As with reactive phosphorus leaching rates, the effects of temperature and water velocity on total phosphorus leaching rates are independent ($F_{2,52} = 1.7966$, $p = 0.1760$, from a two-way AVONA). The mean total phosphorus leaching rate was 4.50 ± 1.053 mg PO_4/hr/g feces.

3. **Design and evaluate scrap iron granule reactors for removing dissolved**

Phosphorus

Experimental design

Preliminary work has been conducted in test the preliminary design and operation of the reactor for removing dissolved P. The moving bed reactor was designed to mechanically abrade iron phosphate and iron oxide precipitates from a sand and granular zero valent iron filtration medium, thereby maintaining its permeability while simultaneously separating sludge from treated effluent. The moving bed reactor has a bed volume of about 140 liters, was constructed entirely of PVC, and has no moving parts. The reactor utilizes a counter-current flow path; wastewater is injected into the bottom of the reactor and flows upward through the sand-iron bed where dissolved phosphorus precipitates in conjunction with the corrosion of metallic iron. Influent water was withdrawn from a wetland distribution pipe and the treatment efficiency was evaluated.

Preliminary results have provided insights in understanding the chemical process of the reactor. Chemical analysis of the dissolved iron indicates that iron III dominants over iron II in the influent water, while iron II is the dominant form during the period when phosphorus is rapidly removed. Chemical speciation indicated that approximately 85% of the iron III exists as FeOH2 (+1) while greater than 95% of the iron II is Fe2+. At circumneutral pH the dominant phosphorus species are HPO4 (-2) and H2PO4 (-1). Calculations of saturation indices suggest that vivianite (iron II phosphate) and strengite (iron III phosphate) are the most likely solid phases precipitating.

Materials and Methods

The moving bed reactor has a bed volume of about 140 liters, was constructed entirely of PVC, and has no moving parts. The reactor utilizes a counter-current flow path; wastewater is injected into the bottom of the reactor and flows upward through the sand-iron bed where dissolved phosphorus precipitates in conjunction with the corrosion of metallic iron. Influent water was withdrawn from a wetland distribution pipe with a 1.5 hp jet pump plumbed into a variable area flow meter and injected into the reactor at a rate of 30-36 liters per min (lpm) at a pressure of 20 psi. Treated water flows out through a internal slotted pipe that contains the sand, and is discharged to a 60-degree trapezoidal flume. The effluent is gauged with a ISCO Model 3200 Bubbler Flow Meter and sampled with an ISCO 3700 Sampler. While the water is moving upward through the sand bed, an airlift pump, operating at one cubic feet per minute (cfm) at a pressure of 14 psi, removes sand from the bottom of the reactor and lifts sand, water, and air through a 1.5-inch side arm pipe and returns the mixture to the top of the reactor. The air is vented out of the top of the reactor and the sand then falls through the upward moving water where the loose particles are rinsed from the sand, and discharged out of a waste line along with a small portion of water. Thus, three flow streams were available for sampling and characterization; influent, filtered-treated effluent, and waste. At an average water injection rate of 30 lpm, a bed volume of 140 liters, and an estimated porosity of 40%, the residence time for water in the reactor is about 2 minutes.

Field chemical parameters including pH, temperature, dissolved oxygen, electrical conductivity, and oxidation-reduction potential (redox) were measured with a Corning

Checkmate 90 meter. Flow through cells fabricated at the UI glass-blower shop were used to divert a small portion of each sample stream past the sample electrodes to prevent interaction between sample water and the atmosphere prior to measurement.

Three water samples representing the three flow streams were hand collected at each time step utilizing three preservation steps for each sample; filtration (0.45μm disk or syringe filter), filtration and acidification, and acidification. The filtered samples were analyzed for anions by ion chromatography by the UI Analytical Science Laboratory utilizing method EPA 300.0 and alkalinity utilizing an auto titrator (QC Titrate, Man-Tech Ass., Inc. PCM-1040/2). Each sample was analyzed only one time because of the expense and time involved. The filtered-acidified samples were analyzed by ICP-AES (Perkin Elmer Optima 3000XL) for total metals, as was the unfiltered sample after a nitric and hydrochloric acid digestion (EPA SW-846, Method 3005). Each of these samples was analyzed in triplicate with the mean concentration and standard deviation plotted as error bars.

On the second test utilizing a 20% iron charge, iron II was analyzed in the field in triplicate immediately after sample collection (Chemetrics Iron 2 No.K-6023 and Milton Roy Spectronic 20). In these samples, iron II concentrations were subtracted from the total iron concentrations as determined by ICP-AES analysis to calculate the iron III concentration, with the sample mean and standard deviation reported. The anions and alkalinity concentrations were not analyzed in the 20% iron test because the change in total phosphorus concentration seemed to adequately document the dominant changes in water chemistry.

Results

The most significant changes observed when comparing influent to treated effluent through the flume were in the dissolved oxygen concentration and redox potential. Influent O_2 was 8 mg/L and flume effluent was 1 mg/L. Concurrently, influent redox dropped from 200-300 mV to flume effluent values of –80 to 0 mV. The water temperature varied with time of day lowering O_2 concentrations due to lower saturation levels at increased temperatures. The pH showed no clear trend in this experiment. Electrical conductivity did not significantly respond to contact with the iron metal.

Figure 24, graphs A-F shows the results of selected chemical analysis. The two dominant chemical changes identified were an increase in dissolved iron concentrations in the flume and a decrease in dissolved phosphorus. Background iron concentration ranged from 0.2 to 0.4 mg/L while flume concentrations ranged from 2.0 to 0.6 mg/L with concentrations generally decreasing towards the end of the data set (Fig. 24A). Influent phosphorus was about 4 mg/L while flume concentrations ranged from 1 to 2 mg/L (Fig. 24C) representing an average of 60% removal over the middle portion of the test (Fig.24D). Phosphate was the only anion that showed a measurable change with nitrate-N and sulfate essentially unchanged (Figure 24B). Calcium was included as it is dominant cation in the water and is sometimes utilized to precipitate phosphorus (as CaO); however, there was no definitive change in concentration in this experiment (Fig. 24E). Alkalinity varied over the test period from 0.003 to 0.0036 equivalents per liter with both influent and flume concentrations having nearly identical changes (Fig. 24F).

The reactor data and meter parameters for the 20% iron charge are shown in Figure 25. It was initially planned to operate the reactor with a 20% iron charge for a similar period to the 10% charge, but Figure 25A shows that the reactor became unstable after about 12 hours of operation when the flume outflow ceased and nearly 100% of the inflow was forced through the waste line before the run was terminated. The reactor was drained and disassembled and filamentous bacteria were observed blocking the internal slotted pipe. The reactor was then reassembled, filled with wastewater and treated with 0.2% solution of sodium hypochlorite. After repeating this process several times with vigorous recirculation the permeability of the reactor screen was restored, indicating that biological fouling was the probable cause of the reactor failure. Nevertheless, the partial run demonstrated some significant differences in reactor operation and performance and the data significantly complement the initial data set.

The pH of the 20% iron run showed a clear distinction between influent and flume effluent with an approximate 0.3 pH unit increase as the water passed through the reactor. Influent pH ranged from 7.3 to 7.6 while the flume pH ranged from 7.6 to 7.9 (Fig. 25B). Dissolved oxygen in the influent was significantly lower than the 10% test with average concentrations of both the influent and flume about 1 to 2 mg/L, with the flume slightly higher than the influent. For the initial 10 hours of the test the average temperature was 25 degrees C, approximately 5 degrees warmer than the initial test. Apparently the sewage treatment plant was unable to maintain adequate dissolved oxygen concentrations in the hot summer weather. Electrical conductivity ranged from 800 to 1000 μS, again with no discernable trend between influent and flume (Fig. 25E). The redox potential of the influent ranged from 50 to 250 mV while the flume redox showed a nearly steady -150 mV, reflecting lower dissolved oxygen concentrations of the influent and greater reducing power from the higher iron concentration in the flume effluent.

Both iron II and III were present in the influent and flume effluent of the 20% iron test. The data suggest that iron III is the dominant form in the influent (Fig. 26A) while Figure 26B shows that iron II is the dominant form in the flume effluent. Total dissolved influent iron concentration ranged from 0.2 to 0.4 mg/L while flume effluent ranged from 0.2 to 0.55 mg/L. However, total iron from the unfiltered-digested samples showed 1 to 1.8 mg/L for the influent and an average of 6 mg/L on the flume effluent (range 1 to 15 mg/L, data not shown). Total iron discharge through the waste line was approximately 1 to 2 mg/L higher than in the flume.

Dissolved phosphorus shows a very distinctive pattern of removal in Figure 26C. Figure 26D shows on average an 80% reduction from the flume effluent and 30 to 40% removal from the waste line as compared to the influent concentration. The plots for calcium suggest a 1 to 2 mg/L lower concentration in the flume effluent (Fig. 26E) Barium was included because it shows a pattern of removal nearly identical to that of phosphorus, even though the total concentrations of the influent are only 0.6 to 0.7 mg/L.

Geochemical characterization

The dominant anions and cations were tabulated in a computer program called

Hydrochem (1997) for representative inflow and flume water samples (Table 9). The total dissolved solids for each of the waters are 428 and 442 mg/L respectively. The data was used to create a piper trilinear diagram showing the distribution of the dominant cations and anions in % milliequivalants per liter (meq), presented a Figure 27. The two data points plot essentially on top of each other demonstrating that little change in the dominant ion balance occurs from the water passing though the reactive iron-sand media. The wastewater may be classified as sodium bicarbonate-chloride water.

The dominant ions, pH, and alkalinity were input into the MINEQL+ computer program for chemical speciation and calculation of saturation indices. (Schecher and McAvoy, 1998). Ions that were identified in the analysis in low concentrations but omitted to avoid unnecessarily complicating the interpretation include aluminum, barium, copper, manganese, zinc, and fluorine.

Two different redox conditions were simulated in MINEQL+. First, redox was calculated using the ion pair Fe3+/Fe2+ for influent and effluent ion concentrations at a fixed pH of 7.14. The pe under these conditions was calculated by the program to be 18 for the influent and 17.9 for the flume effluent. As an alternative to these strongly oxidizing conditions, pe was calculated manually from the platinum redox silver: silver chloride electrode data by adding the standard electrode potential (0.298 V) to the measured electrode potential to determine the Eh of the system. Eh was then converted to pe by the relation:

$$pe = (F/2.303RT)\ Eh$$

where F = the Faraday constant (96.484kJ/V), R = the gas constant (8.314E-03 kJ/K.mol), and T = temperature in kelvins (Drever, 1997). The pH concentration for these waters was varied by the 0.3 pH unit increase identified in the 20% iron test (influent = 7.44 and effluent = 7.74). The resulting pe for the influent and effluent was 8.6 and 2.75 respectively.

Selected chemical speciation results for PO4, CO3, Fe2+, and Fe3+ at pH 7.14 with pe estimated by the Fe3+/Fe2+ ion ratio, are presented in Figure 6. The dominant phosphorus species are HPO4(2-) and H2PO4(1-), bicarbonate (HCO3-) is the dominant carbonate species, Fe(2+) is the dominant Fe II species and the FeOH2(1+) is the dominant Fe III species.

Saturation indices (SI) are useful for determining which solid phases are saturated and unsaturated under chemical equilibrium conditions.

$$SI = \log (IAP)/Ksp$$

Where IAP = the ion activity product and Ksp = the solubility product. When SI > 0, the solid will precipitate, when SI < 0 the solid will dissolve, and when SI = 0, it is at equilibrium. To simplify the output from MINEQL+, only solids with positive SI values are reported.

The SI for solids containing PO4 using pe calculated by the Fe3+/Fe2+ ion pair are presented in Figure 27. Three calcium phosphate phases were identified as well as two iron III species; the hydrous iron phosphate mineral strengite and the anhydrous version of the same mineral (FePO4).

In Figures 28 and 29, SI values for both the influent and effluent waters are compiled using a fixed pe measured in the field. For the influent water six calcium phosphate species are saturated as well as the previous two iron III species. In the flume effluent all the same species are represented with the addition of two iron II species; vivianite and Fe3(PO4)2.

Discussion

Instability in the moving bed reactor has been probablematic throughout multiple tests. Clearly biological fouling was the dominant cause of the failure of the 20% iron test. The sustained 25-degree water temperatures played a significant role in rapid bacterial growth. Reactor instability in the 10% iron test resulted from reloading the reactor with heavily oxidized iron-sand that had washed out of the waste line. Apparently, the density of the media was too high to allow the air-lift pump to circulate the sand. After 40 liters of iron-sand was removed from the reactor and replaced with clean sand, reactor operation was resumed without any additional major problems. However, little phosphorus was removed during this period and so this data was not presented.

The main difference between the 10% and 20% iron tests was the difference in influent dissolved oxygen concentrations. Also the Fe3+/Fe2+ ratio was not measured in the 10% test so we cannot be sure the same phosphorus removal mechanisms were functioning. However, significantly lowered redox potential was measured in each test with a platinum electrode. Because phosphorus removal increased from 60 to 80% by increasing the iron concentration, and lower redox was observed in the 20% iron test, it appears that a chemically reducing conditions played a significant role in the observed phosphorus removal.

Other potential mechanisms for determining the redox potential of these wastewaters include the dissolved oxygen concentration, and the NH4/NO3 ion pair. Dissolved oxygen was not used because the water contains a moderately high biological oxygen demand. Because the water was aerated several hundred meters up gradient from the reactor site it is probably not at equilibrium. Also compressed air was used to circulate the iron-sand media so its concentration should be high at least in the upper portion of the reactor. At least some portion of this aerated water returns through the bed as evidenced by the higher oxygen content of the flume effluent in the 20% test. The NH4/NO3 ion pair may be useful for documenting the redox condition of the influent. However, since the data does not suggest any significant change in the effluent NO3 concentration, it is probably not responding to the corroding iron in the reactor. The very high pe calculated by the Fe3+/Fe2+ ion pair does not appear reasonable considering the low redox values obtained with the platinum electrode. I believe the field measurements are the most useful indication of redox potential.

It appears that Fe2+ was probably dominating the dissolved fraction during the period of rapid phosphorus removal in the 20% test. A possible explanation is that HPO4(2-) is the dominant form of phosphorus at these pHs. However, most of the iron is transported as particles greater than 0.45 μm. Other 2+ cations exhibiting removal from solution include calcium, barium, and, although data was not presented for the sake of brevity, copper and zinc had similar patterns.

The saturation indices for the field-measured pe are probably the most indicative of actual phosphorus precipitation mechanisms. Because large numbers of calcium phosphate species are present in both the influent and effluent, this suggests that there are probably kinetic limitations for precipitation of these solids. The solids of most interest are probably the hydrated the iron phosphate minerals, vivianite and strengite. Both of these minerals have been reported in the iron passivation literature utilizing phosphate to prevent iron corrosion (Gorecki, 1992).

Analyses

Ortho-phosphorous in water was analyzed using ion chromatography with a thermostatted conductivity cell for enhanced sensitivity (USEPA Method 365.2). Total P was analyzed using USEPA Method 365.4.

Results and discussion

Reactor Process

The final process deployment is shown in Figure 25. We used the tertiary effluent of the City of Moscow, Idaho waste water treatment plant (MWWTP), next to the University of Idaho, as a surrogate high flow, low concentration P influent to the process. Our previous work has shown excellent P removal performance using shown aquaculture raceway effluent and holding pond wastewater.

Table 10 shows the average performance for a 24-hr trial conducted at 10 gpm. The average P removal rate was 92%. The decrease in turbidity (62%) and increase in transmissivity at 254 nm (9%) suggest favorable process effluent water quality if UV disinfection is contemplated. Figure 31 shows a graph of the process inlet and outlet water total P concentrations.

Modifications to the prereactor allowed a reduction of the molar ration of iron to phosphorus thereby decreasing costs of operation. Figure 32 shows the relationship of % P removal to Fe:P ratio.

Engineering Economic Analysis

We have completed a final engineering economic analysis for this process applied to high flow, low P concentration aquaculture water using standard techniques. The results are found in table 11.

Trace Analysis of Phosphorus

Total phosphorous analysis by EPA Method 365.4 requires a persulfate digestion. Using direct injection of plain and nitric acid fortified water samples, we compared ICP-MS total P analysis with the EPA standard method. The results are found in Figure 33.

The ICP-MS total P analysis using nitric acid addition (10%) was not significantly different from analysis by EPA 365.4. (Student's t-test, t(20) = 0.117, p=0.907). The direct water sample ICP-MS total P analysis without using nitric acid addition was significantly different from analysis by EPA 365.4. (Student's t-test, t(20) = 1.25, p=0.225) with a slightly low bias. This comparison suggests that direct analysis of nitric acid modified water samples for total P is possible using ICP-MS. The very low detection limits of ICP-MS (<1 μg/L) enhance the quality of data at low levels. Future work is plan on direct the flow of an ion chromatograph into the ICP-MS to allow identification of P species in solution.

Usefulness of findings

The results of this study have shown removal of phosphorus residue from high-flow, low-concentration discharge water is feasible. We are not aware of similar demonstrations of capability at the pilot scale level in the scientific literature. The preliminary engineering economic analysis estimates costs for a commercially constructed treatment process aligned with our research product. Comparative analyses of other lower removal processes suggests the moving bed active filtration is a cost effective method of high flow, low concentration P removal.

Impacts

The innovations developed in this work have been described in a patent application by the University of Idaho. The technology has been licensed by UI for commercialization to Blue Water Technologies (BW). At present BW is working with a consortium of technology providers and civil engineering firms in deployment of pilot studies and formal third party testing. A 30-day P removal pilot trial using this technology is currently being conducted by an engineering firm tasked to examine approaches for achieving tertiary discharge permit levels of 135 μg/L total P from the City of Moscow Wastewater Treatment Plant. The current P release levels of this new $13M treatment facility are currently 0.8 to 2.0 mg/L. Initial 24/7 performance data using moving bed active filtration show >90% removal of P (to >40 μg/L), increase of transmissivity (254 nm) to from 75% to 84%, turbidity at drinking water levels, overall reduction in suspended/dissolved solids, and BOD reduction. In this initial comparison of technologies, the technology produced in this work is the only one achieving the performance/cost criteria goals of the study. The technology developed in this work may have application in closed loop or limited discharge dilution aquaculture operations.

Objective 4. **Improve fecal pellet stability and minimize P loss through feed manipulation**

Results of studies on the effect of specific fish feed binders on feed pellet stability and fecal particle stability prior to capture and removal will provide information that will assist feed manufacturers. Improving the water stability of feed and feces will assist in the removal of solids, thus contributing to reduced hatchery pollution into effluents.

Methods

One hundred rainbow trout (avg. initial wt. 7.5 gms/f) were placed in each of four extended quiescent zone tanks. Fish were acclimated to the experimental tanks and fed the respective feeds for 14 days prior to fecal collection. Fish were fed 3 times per day by hand at 5% body weight per day. Tanks were cleaned at 4:00 PM each day and feces were collected from sections of the extended quiescent zone at 7:00 AM the next day. Experimental diets were distributed using a Latin Square design. Each tank received each diet during a separate four-day collection period. Feces were collected from each tank on four consecutive days buy siphoning. Three sections of the extended quiescent zone were sampled; section 1 is 10.16 cm long, section 2 is 15.24 cm long, and section 3 25.4 cm long. Fecal volume for each section was determined by settling the siphoned material from each section in Imhof sedimentation cones.

The analysis of variance procedure (PROC ANOVA) of the Statistical Analysis System (1993) was use to determine the effect of diet on fecal density. The Ryan-Einot-Gabriel-Welsch multiple range test (REGWQ) was used to determine differences among treatments means. This test was chosen to control type I experimental error rate.

Results and Discussion

There was a significant effect of diet on distribution of solids in the tank, indicating a difference in fecal density (table 12). Fish fed the diet supplemented with poultry oil had the highest proportion of heavy solids (section 1) compared to fish fed any of the three other diets. Fish fed diet 12 also had the lowest proportion of solids in section 3, indicating a low proportion of low-density fecal waste. Diet 14 contained the Superbind binder (CMC) that was found to increase fecal particle size in studies conducted by Dong et al in a previous WRAC study. In the present study, however, fish fed this diet had the highest proportion of low-density feces, suggesting a negative effect on fecal density. The addition of beef tallow to the diet did not change fecal density compared to fish fed the control, fish oil diet. This is contrary to field observations, and might be due to differences in rearing practices, feeding rate or water temperature.

This study indicates that substitution of a portion of the fish oil with poultry oil in the diet of rainbow trout will increase fecal density and improve recovery of solids in the quiescent zone of raceways.

Objective 5. Develop best management practices featuring excretion reduction and efficient removal of both particulate and dissolved P

New ideas proposed by the research team and tested for development of best management practices for solids removal were the use of a baffle to facilitate particle transport, to extend the weir length of the quiescent zone to enhance particle removal efficiency, and to utilize a low cost high-rate filter media to capture solids escaping the q-zone.

Baffles

Based upon previous work, industry input and original ideas, a series of hinged and a moving baffle were designed and fabricated at WSU to test for improved solids transport. The system of baffles was installed in a flume with a 3X3' cross section and 20' long (Figures 34 and 35). The flume is equipped with variable pumping capacity which was used to approximate raceway flow conditions. The baffles were designed to increase bottom raceway velocities while addressing the problems of previous baffle designs such as; high maintenance and reduced fish mobility.

Four baffle configurations were tested. A hinged baffle at 45^o, a hinged baffle at 90^o, a moving baffle and what was termed a modified moving baffle (Figure 36) with a removed cross section were tested. The baffles were constructed of ¾" plywood. Initial baffle dimensions and test angles were selected based on continuity flow calculations solved to give recommended velocities to transport raceway solids.

Hinged baffles were spaced at 4, 7.5, 11 and 14.5 feet (Figure 35). Estimated spacing to provide continuous solids transport. The moving baffles were moved at a rate so as to cover the entire flume during the test duration, approximately 1ft/min (Figure 36). Hinged baffles were supported from above the flume, while the moving baffle was supported on a movable rack above the flume (Figure 35)

Five (5) tests of 90 minute duration were run; 4 baffle setups and one control. At the beginning of each test, 600 grams of sinking trout feed (5/32", ClearSprings Foods) was introduced at 3 evenly spaced intervals along the raceway length. Mass removal and particle residence times (PRT) were then measured by collecting solids captured in a 1000 μm screen basket located in the tail bay tank of the raceway. Velocity measurements were also recorded for cross-sectional areas of the flume. These measurements were used to generate PRT curves, removal and velocity comparisons.

After lab scale experiments demonstrated the effectiveness of the moving and hinged baffle systems to increase particle transport rates, which thereby decreased residence times in raceways, a commercial scale test was performed to verify the performance of the baffles. Experiments were performed at the UI Idaho Springs Research Farm during May, 2003 to evaluate the effects on raceway velocity profiles and solids transport.

A raceway with length, width, and depth dimensions of 100, 9, and 3 ft was selected for use at the facility. This raceway was delineated into two regions, control and test, occupying the first and second 50 feet of raceway length respectively. At the mid-point of each of these regions an area 9 by 5 ft was marked with white survey paint. The flow rate was set at 2.6 cfs, which gave an average channel velocity of 0.09 ft/s, both indicative of industry practice.

Full scale baffles were constructed out of ¾" plywood in the same manner as the lab scale prototypes. A rolling carriage was constructed for the moving baffle that rode along raceway wall tops was fabricated from 4" wood timbers, casters, and 2" iron angles to keep the carriage on track.

The moving and hinged baffles increased bottom velocities respectively by 1,200% and

700% above the control. The moving baffle induced a velocity of 0.12m/s, which is above the minimum recommendation of 0.1m/s. However, the hinged baffle’s 0.7 m/s fell below this value by 0.03 m/s. Improvements in removal above the 17% of the control were also observed for both systems with 83% and 60% for moving and hinged baffles, respectively.

A small mock up baffle was built and tested in February 2004 under simulated raceway conditions at the University of Idaho’s Aquaculture Research Institute. A flume 2’x 2’x 30’ long fitted with a variable speed water pump allowed for water flow velocities that replicated those previously reported for Southern Idaho raceways. A major concern in using a moving baffle in densely stocked raceways was over crowding of fish as the baffle traveled down the raceway. To address this issue an automatic fish release device was devised consisting of a 4” wide hinged flap attached to the entire bottom edge of the baffle. The flap would automatically lift as the baffle traveled over a lobe placed in the bottom of the flume, thus allowing crowded fish to easily swim under the baffle with the flap up. Tests were run to maximize flap size for fish release while not interfering with baffle travel over the lobes.

Using information from the U of I flume tests a full scale baffle was constructed and installed at the University of Idaho, Idaho Springs research farm in April 2004. Visual observation has shown the effectiveness of the baffle in moving fecal particles down the raceway to the quiescent zone and shown the ability of the fish to pass and not overcrowd. In July, further modifications were made to the baffle including disabling the flap as fish were observed to pass effectively without it. The second modification was to reduce the side and bottom clearances while notching out the bottom corners. This modification allowed for improved solids transport and scouring, while not affecting fish passage.

A second generation of the baffle was designed, fabricated and tested (figure 37). The design has incorporated several new features that address some operational problem encountered with the first prototype in the early tests. The baffle is a sheet of aluminum 1/8th inches thick attached to an aluminum frame. The frame rolls on two sets of wheels running on both the upper and lower surfaces of a 1.5” x 5.5” track attached above the water line on both side walls of the raceway wall and running the entire length of the raceway. The entire baffle rotates on an axis (axis 1) that runs along the upper edge of the baffle and is capped on each end with a wheel. The wheels on axis 1 rides in a groove on the top surface of the wall track. A second, truncated axis (axis 2), running parallel to axis 1, but located eight inches in front (down stream) and six inches below, is also capped with a set of wheels that ride in a groove on the bottom surface of the wall track. When both sets of wheels are in place on the wall track it locks the baffle body in an upright, operating position perpendicular to the raceway floor.

The baffle is sized to fit just inside the raceway with a two inch reveal from the sidewalls and bottom floor and projecting 12 inches above the water surface. A second sheet of aluminum, eight inches wide and running across the baffle bottom, allows for adjustment of the bottom opening. Strips of flexible rubber are attached to the side ends of the baffle body and rub against the raceway sidewalls blocking any water from getting by and automatically adjusting for variations in the sidewall dimensions. Since the baffle moves down the raceway much slower than the water, this blocks the normal free water flow down the raceway, forcing it to go through the small space under the baffle at a greatly increased velocity. The hydraulic scouring caused by the velocity increase is what cleans the raceway bottom and continuously sweeps debris down the raceway as the baffle moves along. The baffle itself is slowly driven down the raceway by the pressure of the water backed up behind it. As the baffle moves down the raceway it would slowly crowd the fish into a smaller and smaller area if not for a small six by six inch opening in each of the two bottom corners that act to continuously release fish upstream.

When the baffle reaches the end of the wall track the wheels on axis 2, running on the bottom wall track surface, run off the end of the track while the upper wheels are kept on with a stop when they reach the end eight inches later. With the lower wheels off the track this allows the baffle to rotate around axis 1, partially swinging up and away from the raceway floor and releasing any water still blocked. Two pontoons positioned on the upstream side of the baffle body are then able to rotate the baffle farther around axis 1, actually lifting the baffle out of the water so the baffle body is parallel to the water surface and ready for return to the head of the raceway. Once again at the head of the raceway the wheels on axis 1 can be locked in place with a stop and the baffle can then be flipped or rotated the rest of the way around axis 1 until the baffle body drops back in the water ready for the current to force it back down stream until the wheels on axis 2 come around and slip into the groove on the bottom side of the wall track and lock the baffle body into the operating, perpendicular position.

Motion control of the baffle up and down the raceway is accomplished by slowly paying out a rope tied to a halo that is attached to the baffle. The halo is a stiff rod, attached on each end of axis 1 just outside the wheels that projects from axis 1 parallel to the side wall for three feet and then angles into the center where both sides meet. The halo allows the baffle body to rotate 360 degrees without being detached from the rope.

The baffle was shipped to UI's experimental fish farm in Southern Idaho three times for tests. Although improvements were observed, the baffle is still not function properly due to the increased resistance to moving after the modification.
Nonetheless, the improvements have further demonstrated that the concept is feasible. A commercial company has been contacting Washington State University to license the technology for commercialization with additional refinements.

Weir modification

During the site characterization portion of the research it became evident that weir overflow rates from the raceway quiescent zones were well above recommended quantities. Excessive overflow rates can create a scouring effect near outlet areas which reduces effective settling volumes and can contribute to reduced removal efficiencies.

To address this problem a weir modification was designed, fabricated, installed and tested at site 2 (Figure 38). The modification consisted of a series of troughs meant to distribute overflow water over a greater lengthwise distance. This retrofitted distribution is meant to reduce localized high velocity/energy overflow thereby reducing the scouring effect and restoring settling velocity volume and removal efficiencies. The testing scheme was a proof of concept type, and involved testing solids removal efficiencies, velocity profiles and phosphorous capture in the quiescent zone. The modification reduced overflow velocity from 3671ft3/hr/m to 706 ft3/hr/m and q-zone velocity from 0.26 ft/s to 0.16 ft/s. Particle size escaping q-zone was reduced by 11µm. However, no improvement in removal efficiency was observed.

High-rate filtration media for use in raceway applications

Laboratory Testing

The fuzzy filter media was run at 40 gpm/ft2 and head losses were 2.5in at time 0 min, 5.5in at time 30 min, and 6.75in at 1hr. It was the only media that exhibited any losses. Head loss measurements were negligible for all reticulated foam media during the duration of the 1 hr. tests, which were conducted at 100 gpm/ft2. Results for the particle size captured are shown in Figure 39.

Although all reticulated foams were easily able to handle the hydraulic loading they were not all acceptable in their particle capture. For example, in reference to figure 39, the average size captured by the 10 and 20 ppi foams during the test duration was 217 and 161µm, above the target 100µm. The 10 ppi appeared to have little effect on the influent particle size distribution at all. However, while the 20 ppi initially captured down to 120µm, the 214µm spike at the conclusion of the test is believed to be indicative of the solids front breakthrough in the filter bed. The 30 and 45ppi materials both performed nicely initially capturing particles down to 75 and 74µm, while the 45ppi material maintained the capture at 72µm up to the test's end, the 30 ppi had a solids front breakthrough as well visibly in the effect as well as the 163µm spike. The fuzzy filter media performed best in terms of particle size capture with an average of 51µm.

These tests were the essential first test in evaluating an suitable high-rate filtration media for this application. In terms of head-loss and flow-rate all reticulated foams easily handled the 100 gpm/ft2 loading. The particle capture was the first eliminating factor. The 10 and 20 ppi materials have been eliminated because of the high average discharged particle size. Despite the solids breakthrough at the conclusion, the 30 ppi material performed nicely, and was selected for further testing on raceway wastes. The 45 ppi material appeared most suitable as it was able to maintain its particle capture through the duration of the test with negligible head loss.

Although the fuzzy media performed best in terms of particle size reduction the hydraulic loading was only 40 gpm/ft2 and head losses quickly developed. While initially investigating this material it was hoped that greater hydraulic loadings could be achieved by reducing the bed compression, since the acceptable particle capture size for the raceway application is 100µm. An order of magnitude greater than what has been reported for this media when use in a tertiary waste water polishing capacities. In wastewater applications the media is frequently housed in a pressurized vessel, and a mechanism allowing for variable compression of the bed. Resulting in greater particle size reductions than those measured here, at hydraulic loadings up to 40gpm/ft2. To overcome head losses these units are also equipped with process control backwashes, powered by an air blower to scour the media, removing captured solids and directing them to further treatment. Currently many farms have limited electrical infrastructure to support such functions.

For this application, the simplicity of the filtration mechanism is essential for success. Ideally, any filtration operation would be able to operate at atmospheric pressure, high hydraulic loads, and have simple back-washable properties. For these reasons the fuzzy filter media is not currently suitable for this application.

Field Testing

The next phase, field testing, was completed with the 30ppi material. The average influent and effluent particle size during a comparable test are shown in Figure 40. Figure 41 illustrates the filter bed sections and designations as well as median captured particle size in each region. From top to bottom, the filter regions were denoted T, MT, MB and B. TSS and particle size collected from each filter region are shown in Table 14. Based on the collected TSS samples from the known volume of wash water the solids captured in each section were calculated, including the cumulative captured solids also. Then knowing the percent P per TSS and the influent TSS, the percent capture of influent TSS and the effect on P discharge have also been calculated.

The average effluent particle sizes of; 91, 95, 92 and 90um shown in Figure 40 are all below the 100um target value. They are also below the average laboratory value observed in the later part of that test; 107 and 172um. It is believed that the viscous, adhesive, bridging nature of the organic matter present in the raceway effluent is more readily intercepted than the simulated effluent's crushed and sifted feed. That is the raceway effluent is actually more conducive of being trapped and lodged within the foam's matrix than the simulated feed, which is a welcome discovery. The extended nature of the field test allowed the build up of solids, which was reflected in the head-loss of 6in. at the conclusion of the 16hr test.

The filter bed and solids analysis also provided encouraging results, table 14. As one might expect there was a noticeable gradation of captured particle sizes from 196, 145, 143, to 133um as one progresses downward through the bed. This trend was also followed by solids capture as more material was retained in the upper portions of the bed, indicated by the retained total masses of 6512, 2032, 1088, 1232mg. This capture resulted in a cumulative reduction in TSS discharge of 31% and the same corresponding reduction in overall P discharge, 31%. This reduction agrees with estimated P reductions of 20 – 40% if solids capture improvements could be made.

Could this filtration technology be applied to the entire raceway flow to reduced P discharge by this amount on a large scale remains to be seen? But, this component of the research has proven the applicability of this media in terms of loading capacity, head loss and particle size reduction, solids and finally P discharge removal. The factors which must be addressed in order implement on a full scale are basic design considerations including; reactor design, plumbing, and the backwash mechanisms. Preliminary designs and operational criteria have begun and will continue to be developed.

Objective 6. Evaluate the best management practices in commercial settings

The project work group has decided the center piece of the management practice is the moving baffle. After lab scale experiments demonstrated the effectiveness of moving and hinged baffle systems to increase particle transport rates, which thereby decreased residence times in raceways, a commercial scale test was performed. During May, 2003 experiments were performed at the UI Idaho Springs Research Farm to evaluate effects on raceway velocity profiles and solids transport. The moving and hinged baffles increased bottom velocities respectively by 1,200% and 700% above the control. The moving baffle induced a velocity of 0.12m/s, while the hinged baffle managed 0.7 m/s. Improvements in removal above the 17% of the control were also observed for both systems with 83% and 60% for moving and hinged baffles, respectively.

A small mock up baffle was built and tested in February 2004 under simulated raceway conditions at the University of Idaho's Aquaculture Research Institute. Using this information a full scale baffle was constructed and installed at the University of Idaho, Idaho Springs research farm in April 2004. Visual observation demonstrated the effectiveness of the baffle in moving fecal particles down the raceway to the quiescent zone and the ability of fish to pass.

A second generation baffle was designed incorporating several new features to address operational problems encountered with the first prototype. The baffle was tested at UI's experimental fish farm three times. Although improvements were observed, the baffle is still not function properly due to the increased resistance to moving after the modification. Nonetheless, the improvements have further demonstrated that the concept is feasible. A commercial company has contacted Washington State University to license the technology for commercialization with additional refinements.

Outreach

One popular press article in 2 publications (Aquaculture Magazine and Waterlines) was published. Additionally, demonstration experiments were conducted dealing with phosphorus levels developed in pond and raceway culture and disposal of these phosphorus effluents on field crops. This has been recognized as a Best Management Practice in the newly released EPA Guidelines for Disposal of Aquaculture Effluents. Furthermore, the website http://ag.arizona.edu/azaqua/extension/BMPs/Final_EPA.html was recently created to provide the new EPA Guidelines to aquaculture producers in the Western Region (and beyond). EPA determined that the most effective measure for reducing phosphorus in discharges was to limit and reduce solids, minimize release of uneaten food and dead animals and to develop and maintain a BMP plan for each farm. Considering that much of our research in this project support these exact determinations, we feel that we have been directly on the right track all along. The project will continue to develop the formal materials and assist producers to develop their individual BMPs' and institute them on their farms.

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McIntosh, D. 2003. - Use of inland shrimp farm effluent for crop irrigation. University of Arizona

SUBMITTED BY: ______________________________ __________

Shulin Chen, Work Group Chair Date

APPROVED: ______________________________ __________

John Colt, Technical Advisor Date

Appendix A:
Figures

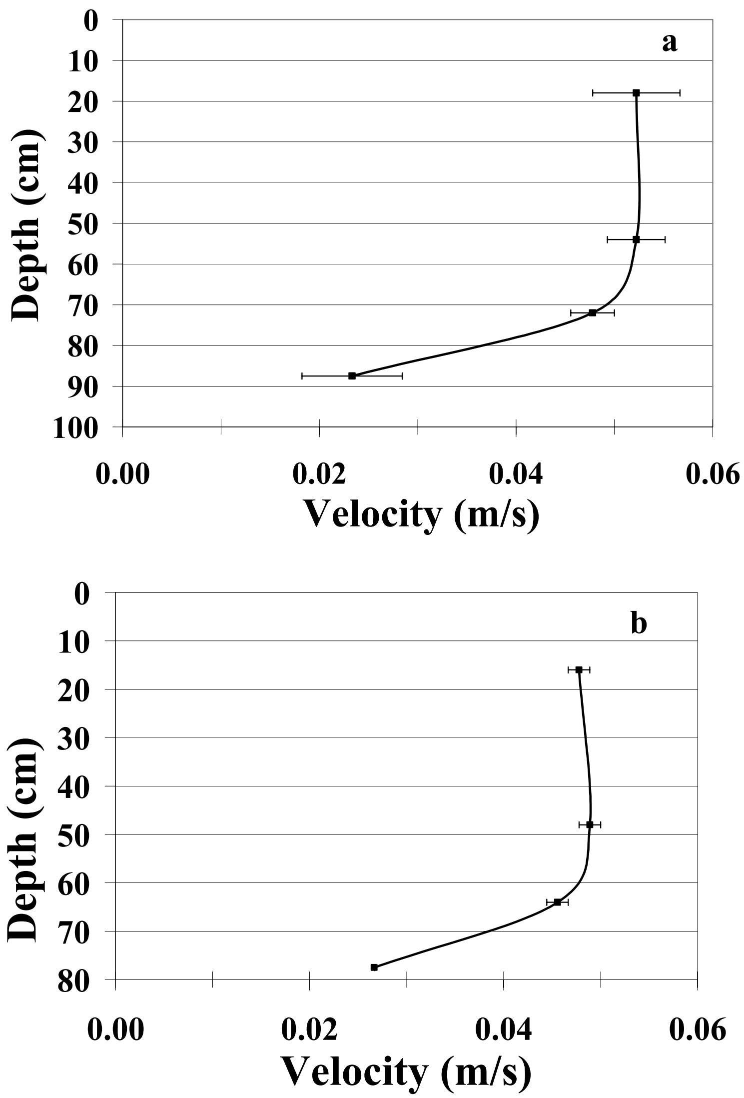


Figure 1: Farm 2 (a) and Farm 4 (b) raceway velocity profiles
Note: Profiles are shown from the free surface (at depth of 0 cm) down to the raceway bottom, and total water depths at Farms 2 and 4 were 90 cm and 80 cm, respectively.

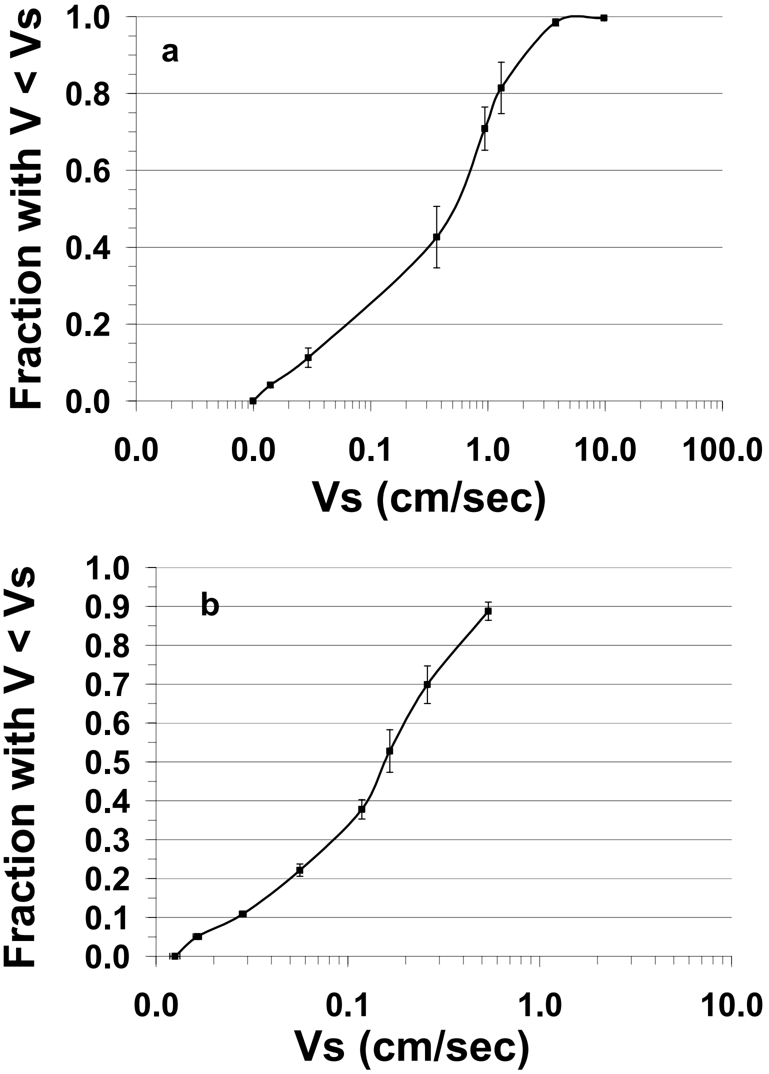


Figure 2: Mass fraction of particles with settling velocity (V) less than the indicated terminal settling velocity (Vs). Average large (a) and small (b) particle settling curves
Note: Settling calculations performed as described by Wong and Piedrahita (2000).

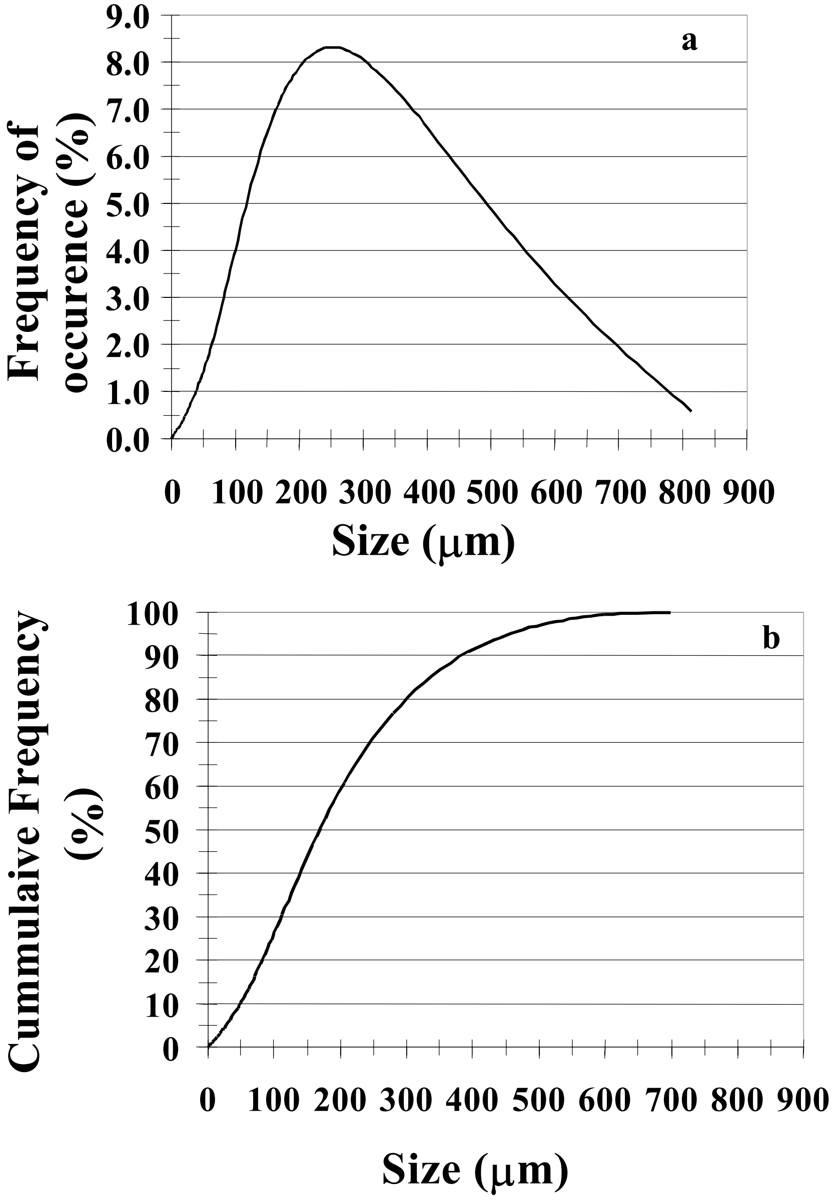
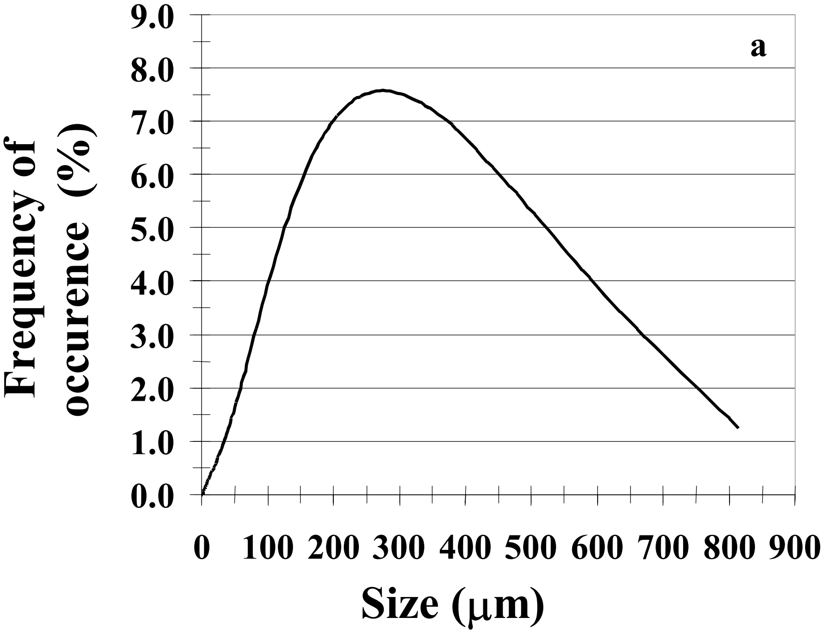


Figure 3: Farm 2 (a) Frequency and Cumulative (b) particle size distribution curves



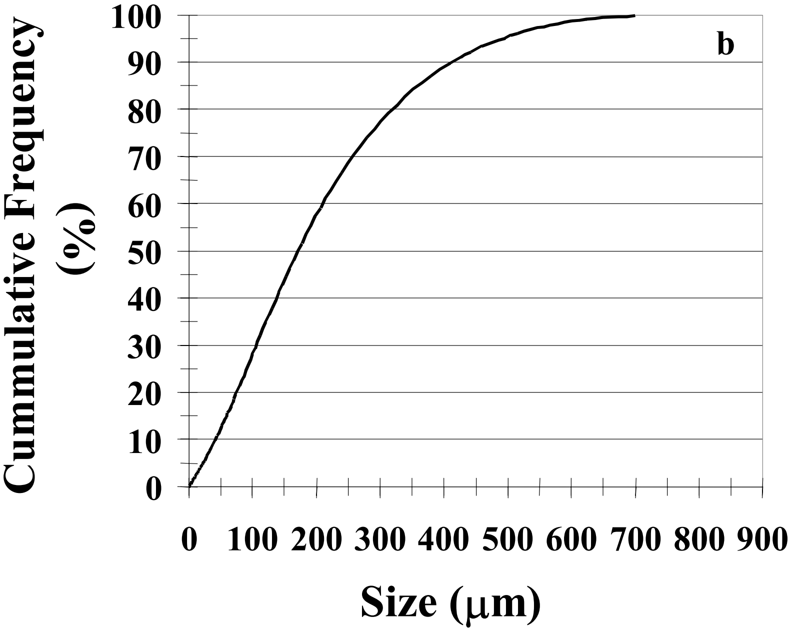


Figure 4: Farm 4 (a) Frequency and Cumulative (b) particle size distribution

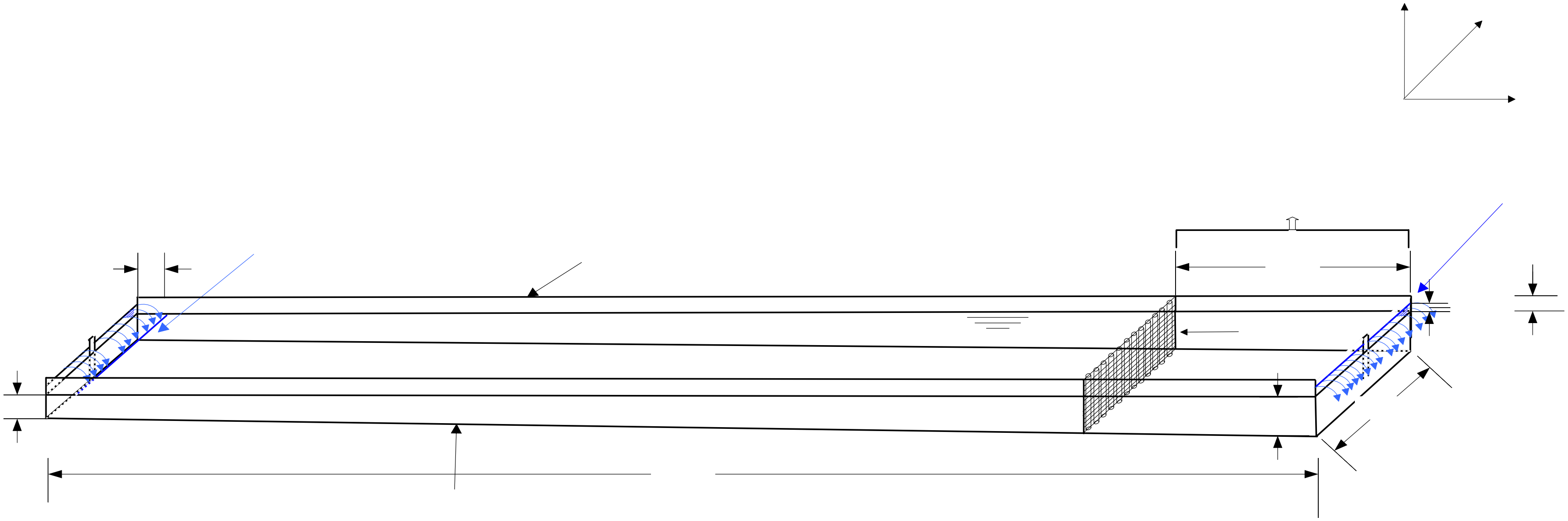
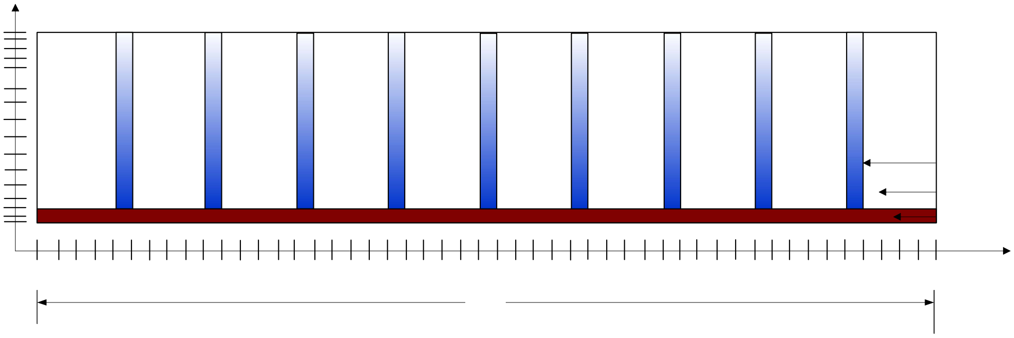


Figure 5: Schematic diagram of a raceway (Slope =0.01)

2.5 cm OD (¾ in pipe nominal size)
1.2 cm of space between the pipes
Width of the wood frame ~9.0cm

pes

A. Real screen



B. Model screen

Figure 6. Divider screen between the rearing area and the QZ.

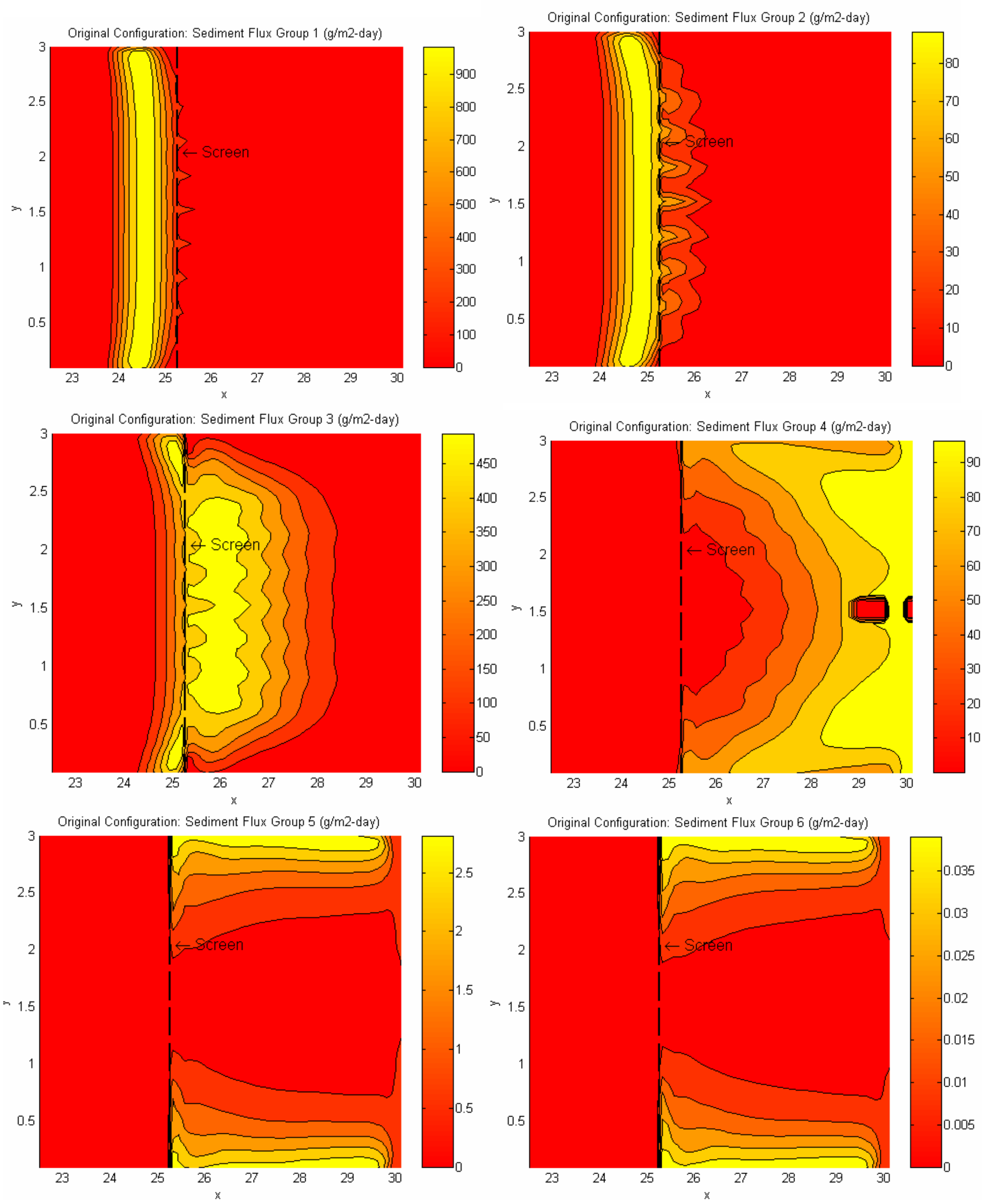


Figure 7. Sediment fluxes (g/m^2.day) for the different particle groups of a preliminary run for the original system. The graphs show a top view of the QZ and an area just upstream from it. The graphs are not to scale. The color represents the sediment flux as indicated on each of the graphs.

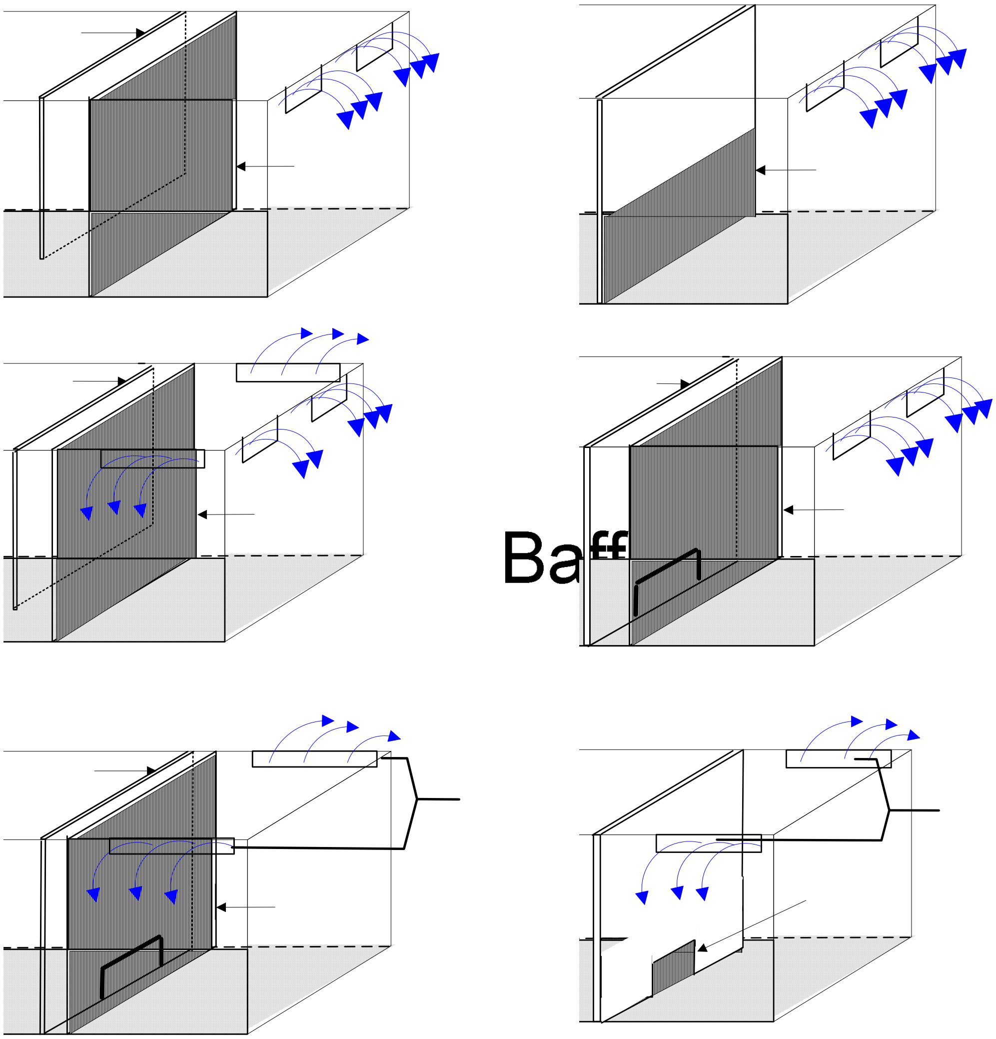


Figure 8. Schematic diagram of the QZ of the design alternatives considered. The drawings show the approximate location and shape of the screen, baffle, and effluent

S

Al

Baffle

Figure 9. Funnel and siphon system used to sample influent q-zone water during q-zone size testing. Left shows q-zones 1.5 and 2 times the current length and right shows 1.5 current q-zone length.

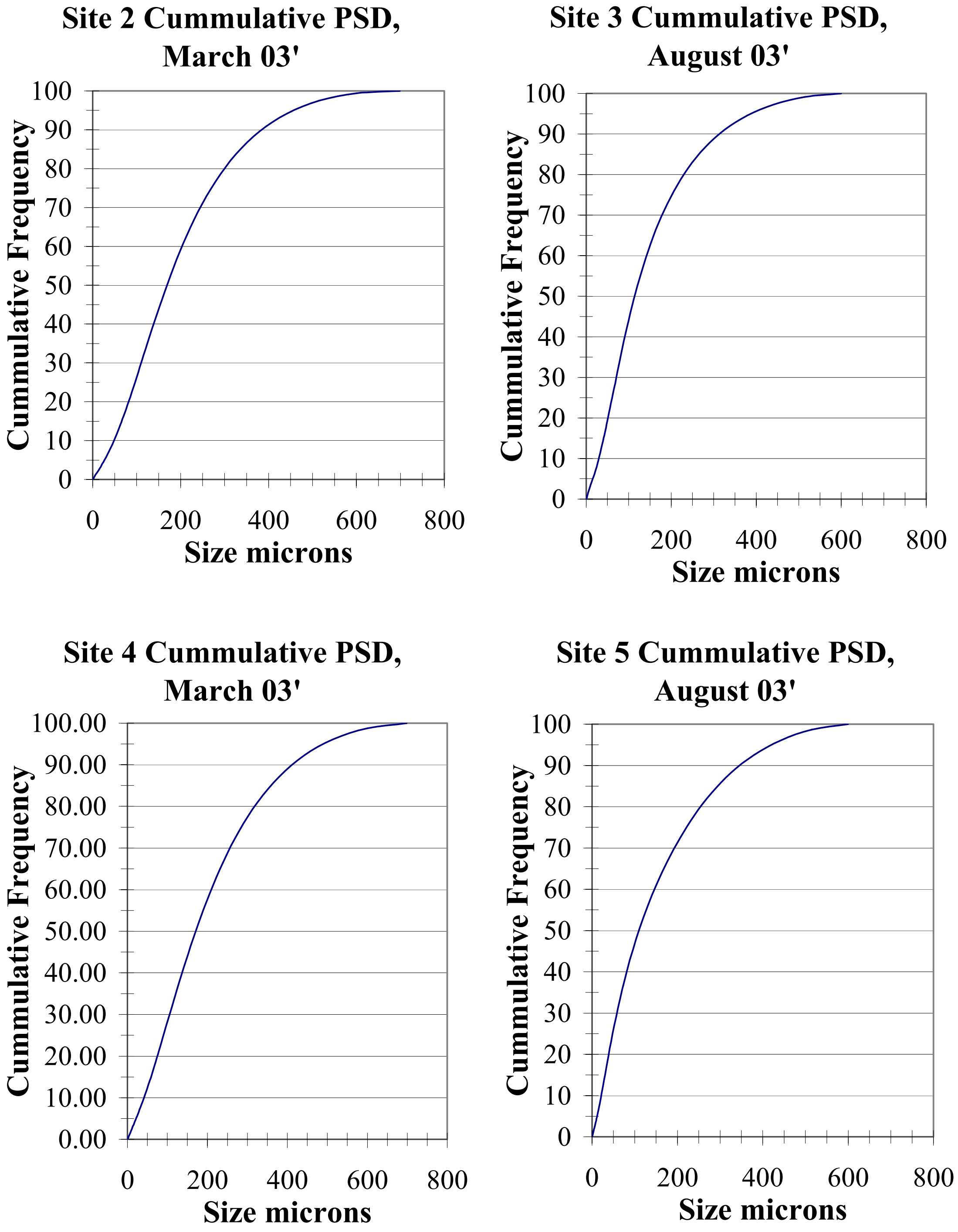


Figure 10: Q-zone effluent particle size distributions

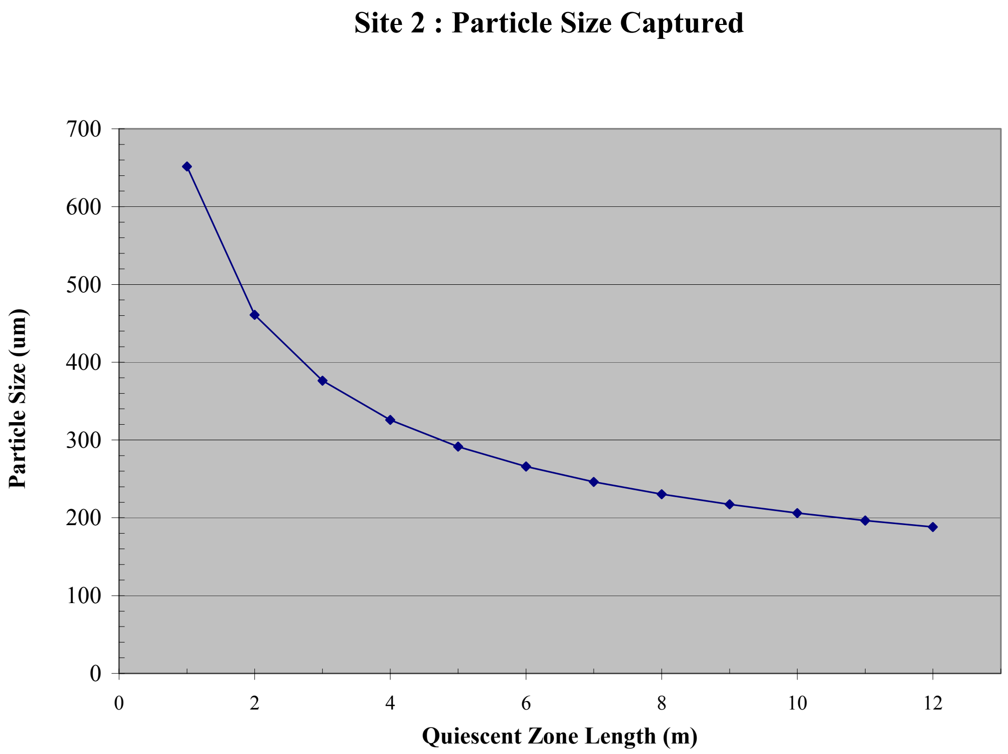

Site 2 : Particle Size Captured

Figure 11: Particle size captured as a function of q-zone length

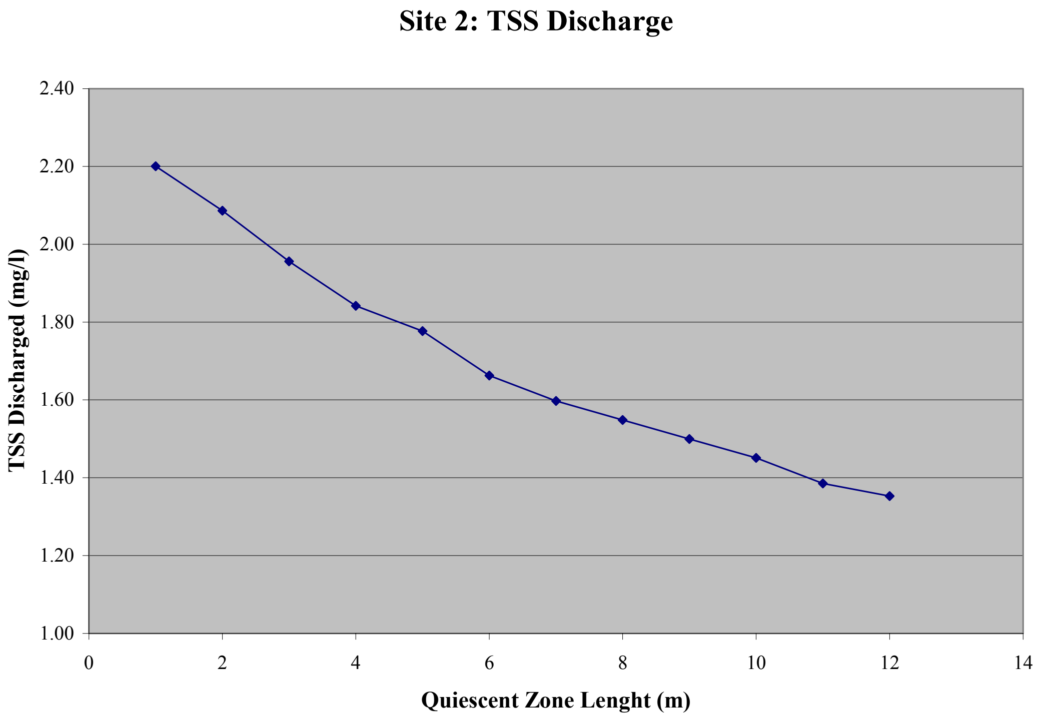
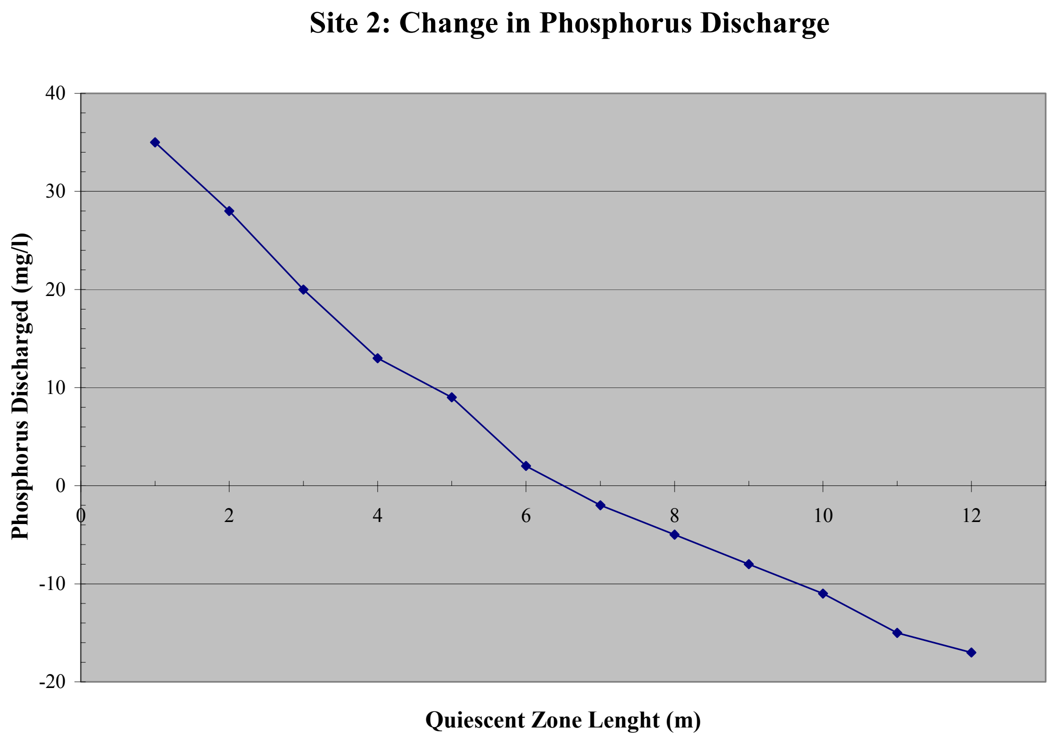

Site 2: TSS Discharge

Figure 12: TSS discharged as a function of q-zone length



Figures 13: Phosphorus discharge as a function of q-zone length

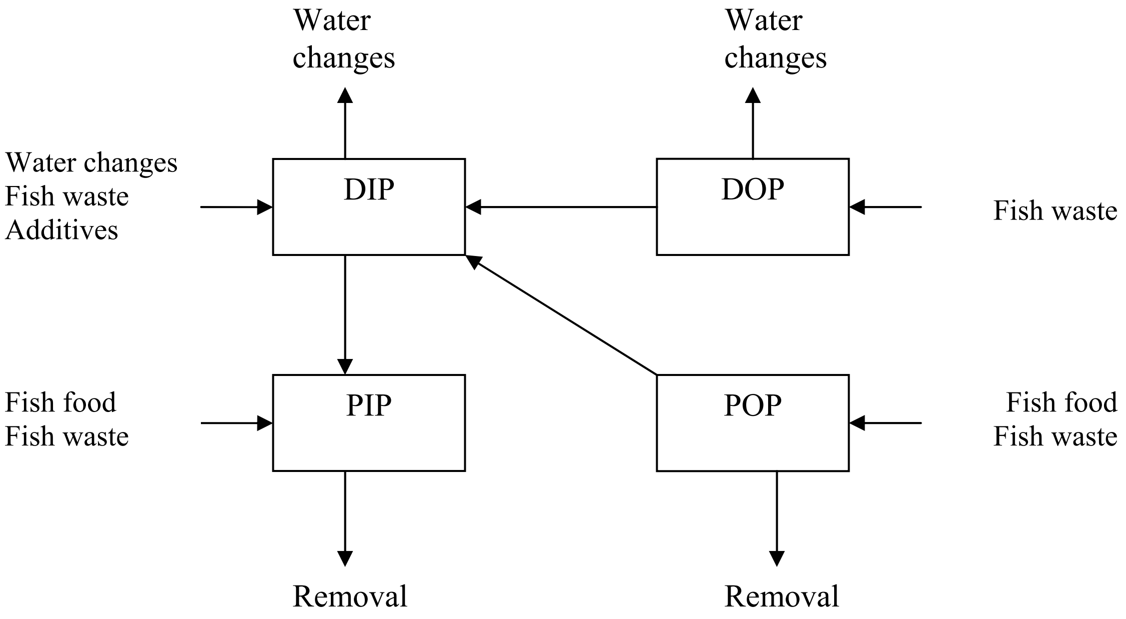


Figure 14: Forms of phosphorus and routes of entry into the water

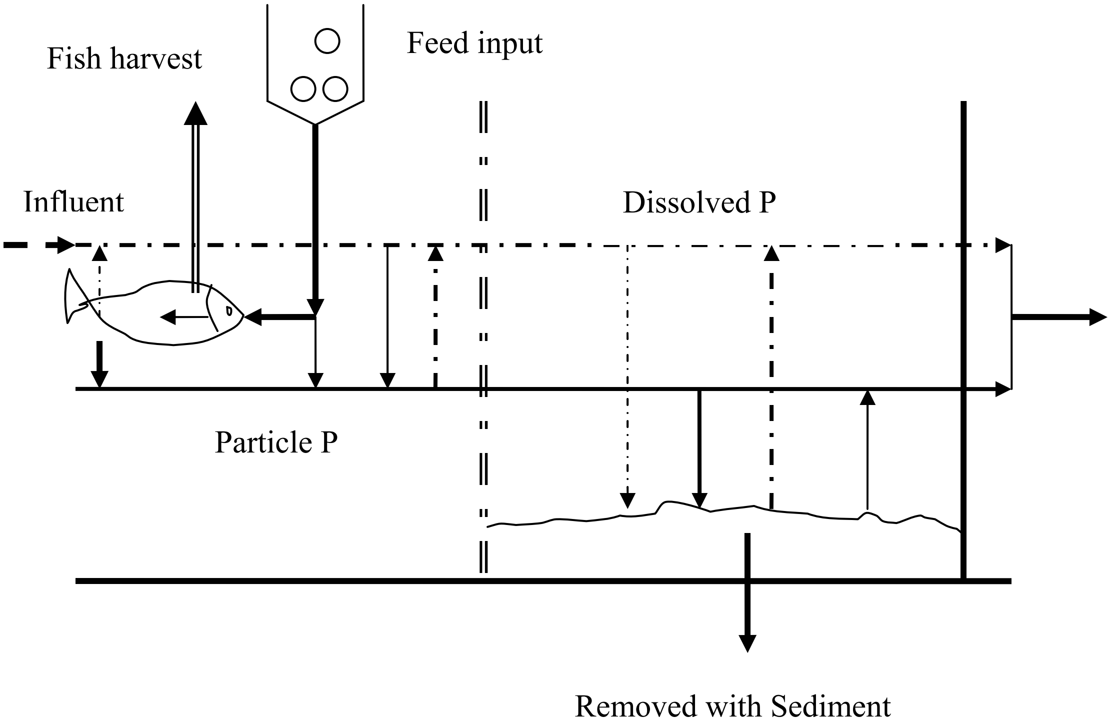


Figure 15: Cycling of phosphorus within the raceway

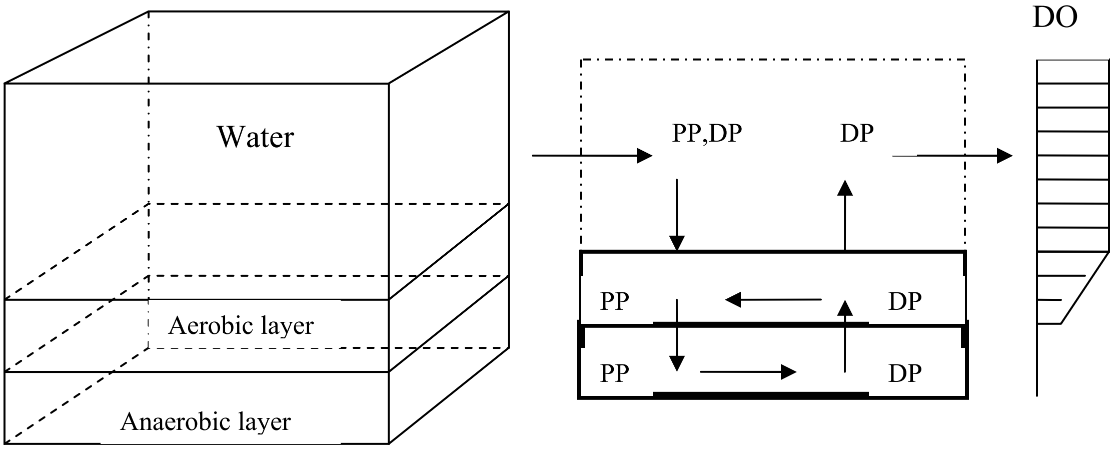


Figure 16: Mass balance box model for phosphorus dynamics in the sediment

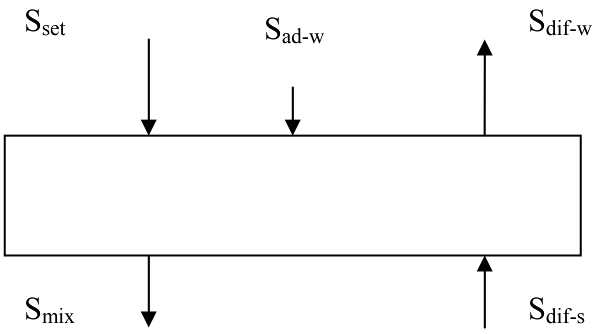


Figure 17: Total phosphorus mass balance in the aerobic layer

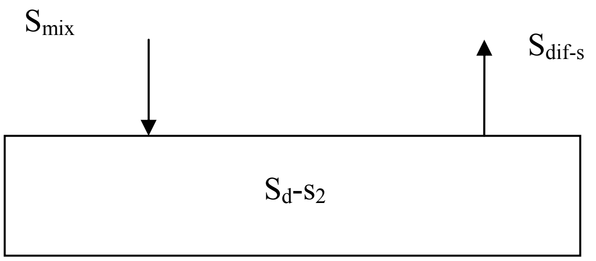


Figure 18: Total phosphorus mass balance in the anaerobic layer

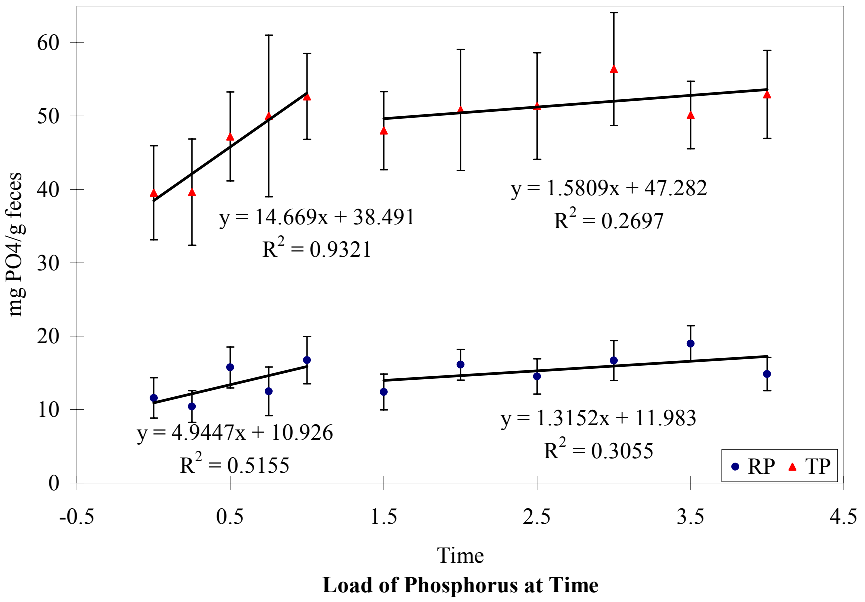


Figure 19: phosphorus leaching from trout feces

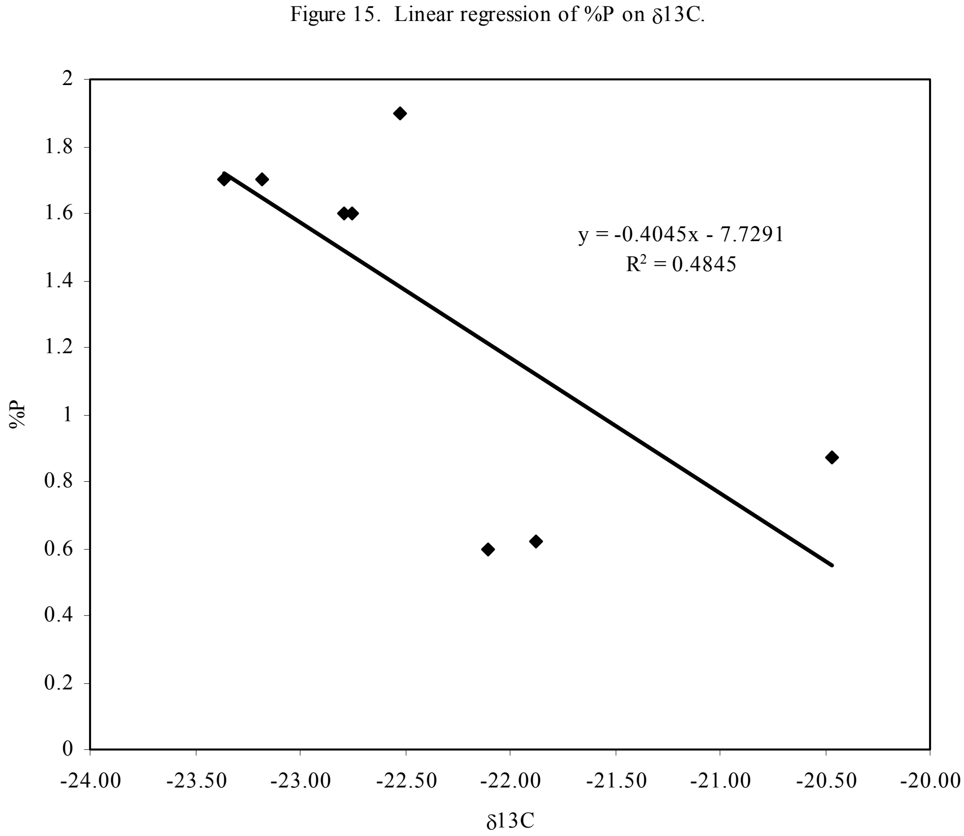


Figure 20. Linear regression of % phosphorus on $\delta^{13}C$

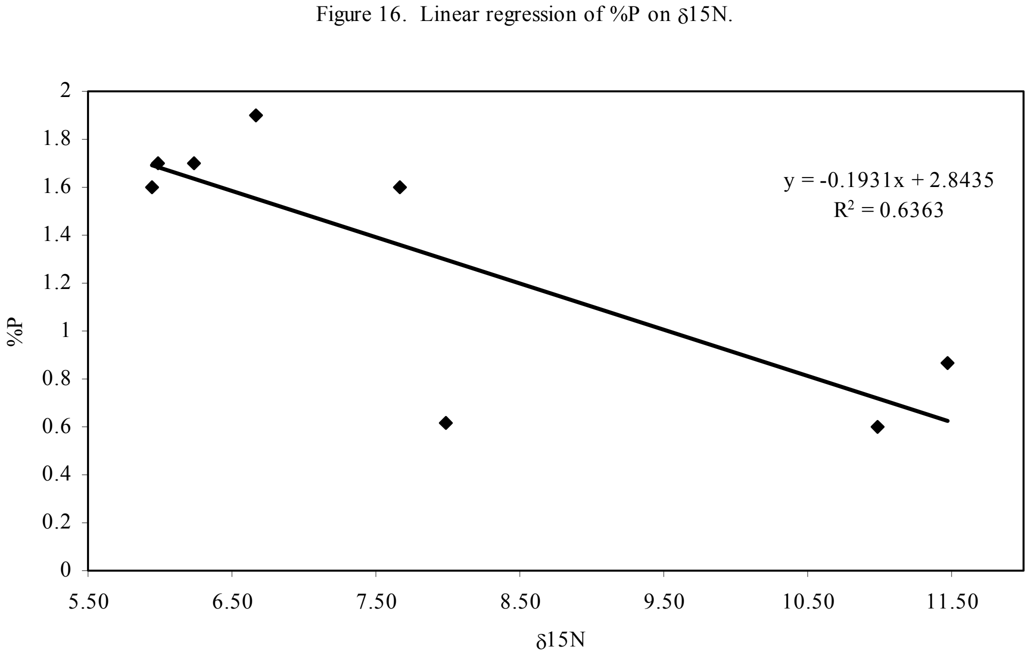


Figure 21. Linear regression of % phosphorus on $\delta^{15}N$

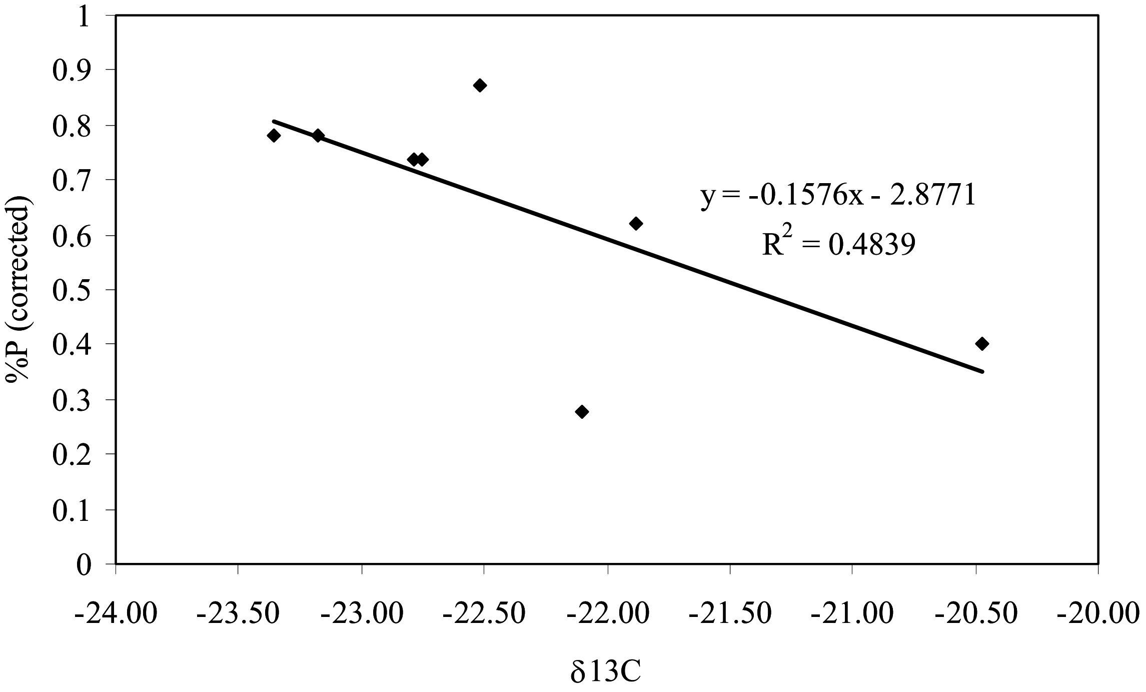


Figure 22. Linear regression of % phosphorus (corrected) on δ^{13}C

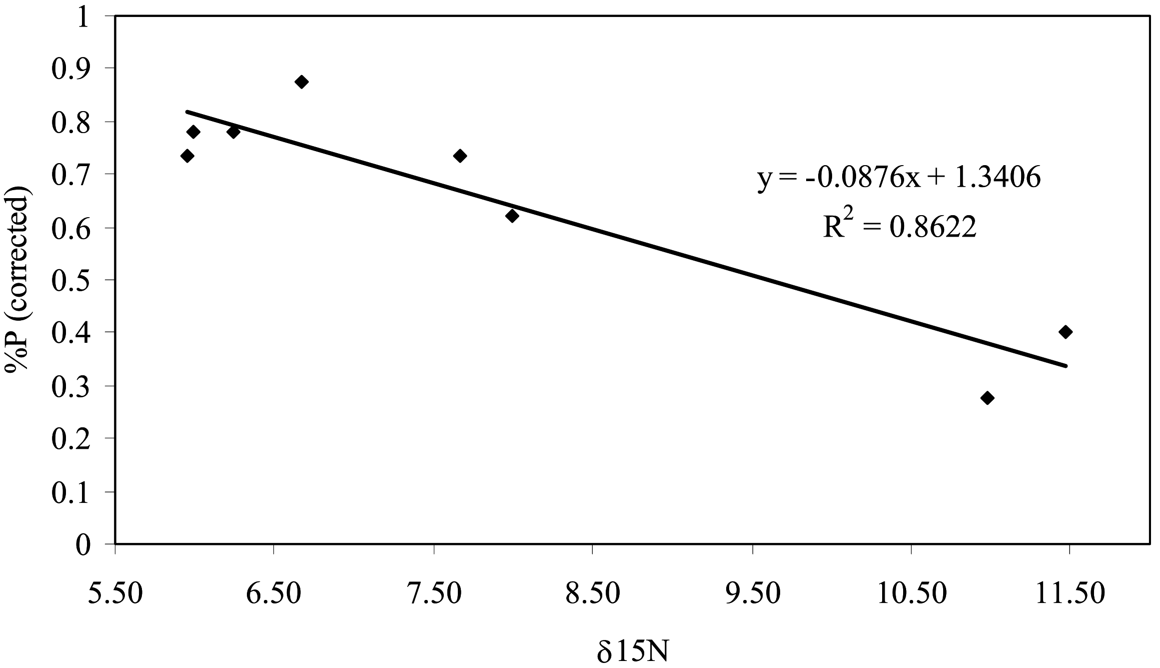


Figure 23. Linear regression of % phosphorus (corrected) on δ^{15}N

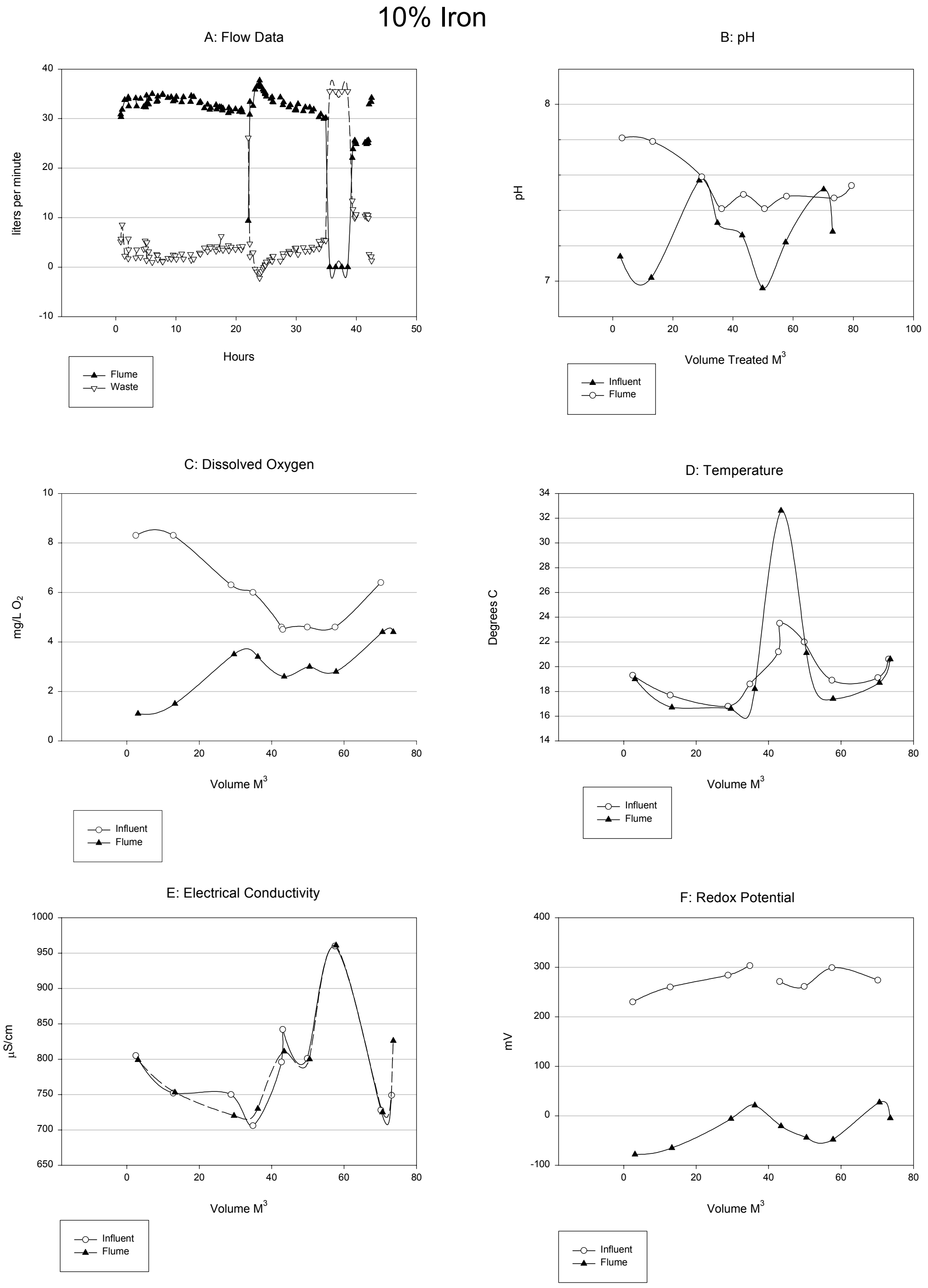


Figure 24. Field measured parameters for the 10% iron experiment.

20% Iron

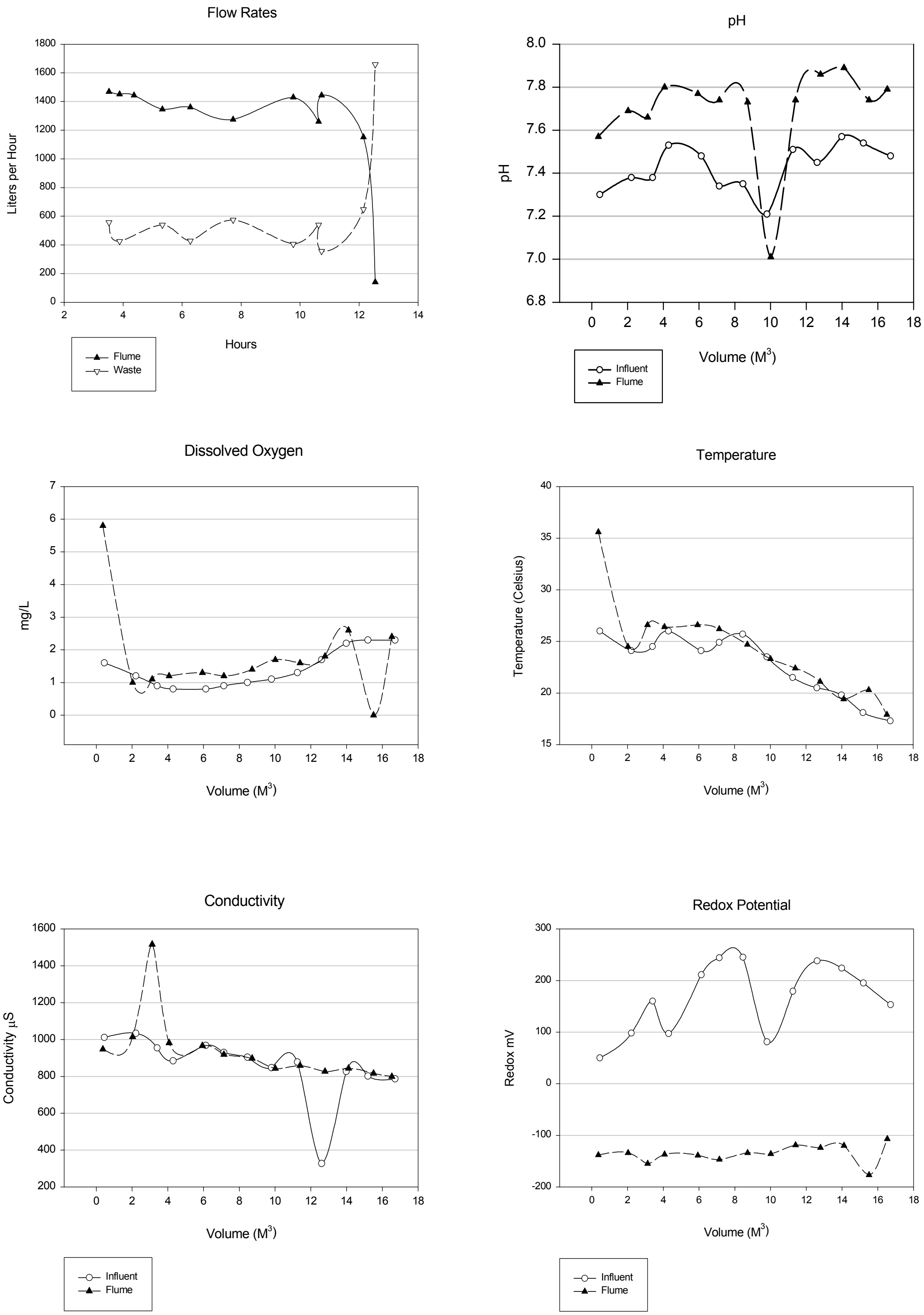


Figure 25. Field measured parameters for the 10% iron experiment

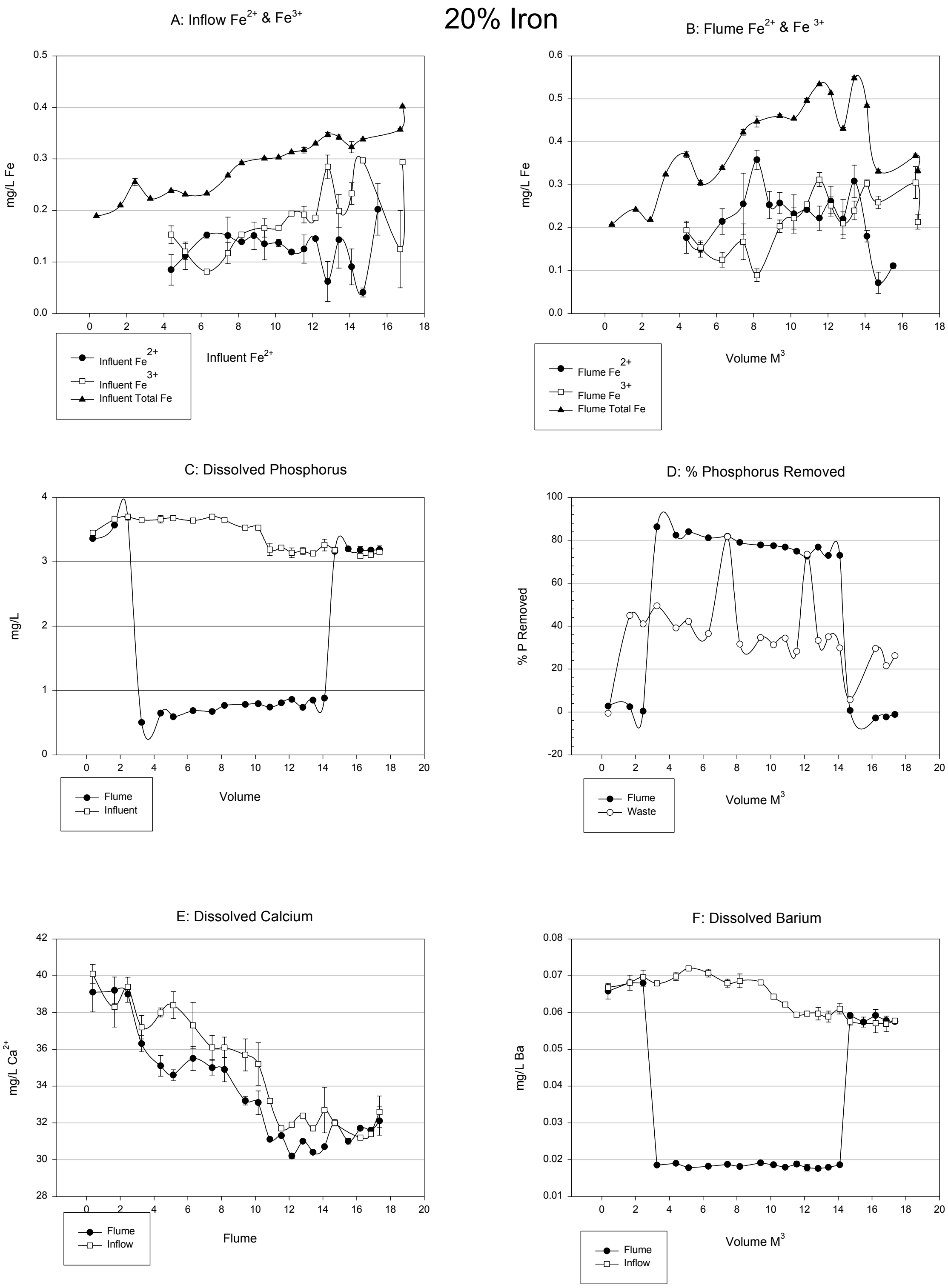


Figure 26. Selected laboratory analysis for the 20% iron experiment.

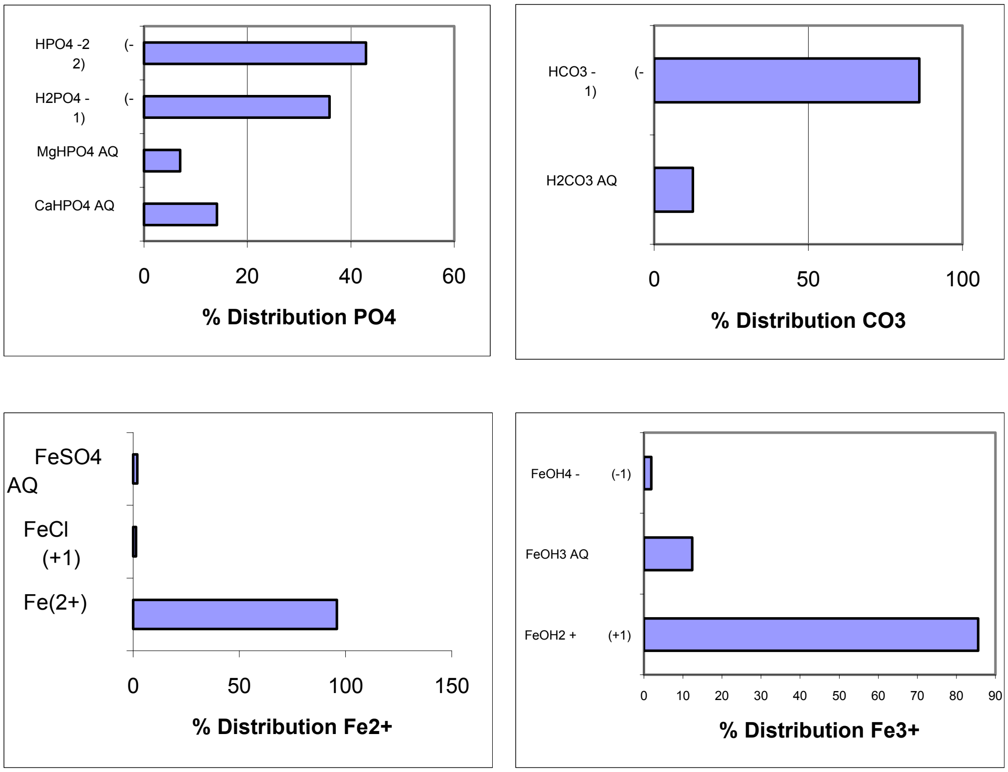


Figure 27. Chemical speciation results for the reactor flume effluent calculated by MINEQL+. Fixed entities include pH = 7.14 with pe = 17.9 as calculated by Fe3+/Fe2+ redox pair.

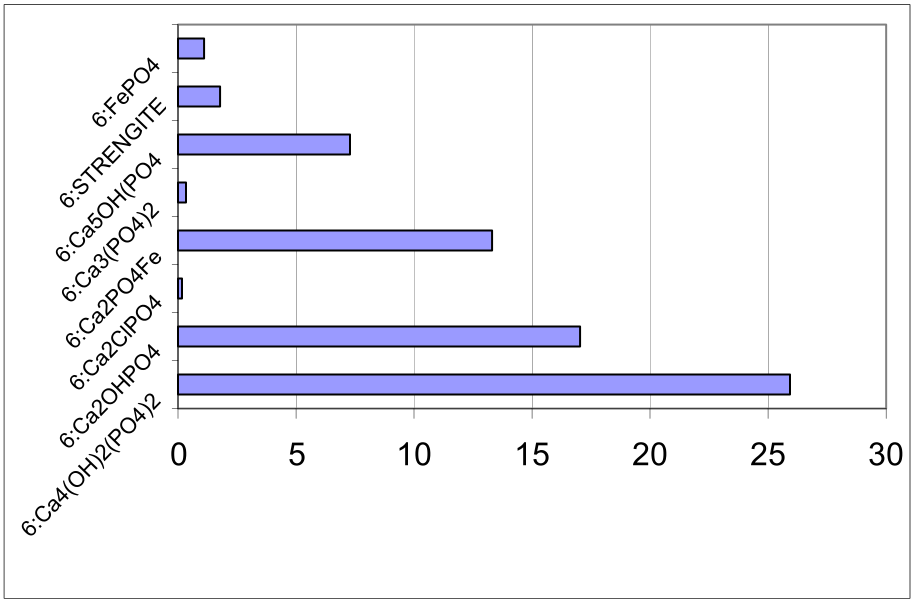


Figure 28. Log saturation indices for reactor influent as calculated by MINEQL+. Fixed entities are pH = 7.44 and pe = 8.6.

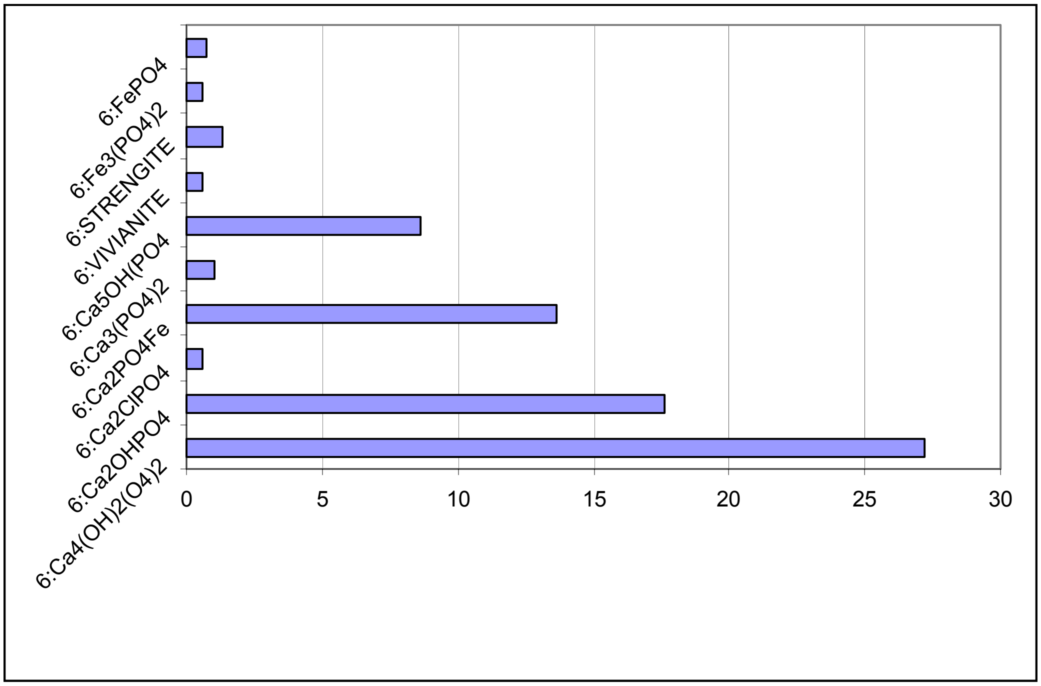


Figure 29. Log saturation indices for reactor flume effluent computed by MINEQL+. Fixed entities are pH = 7.74 and pe = 2.75.

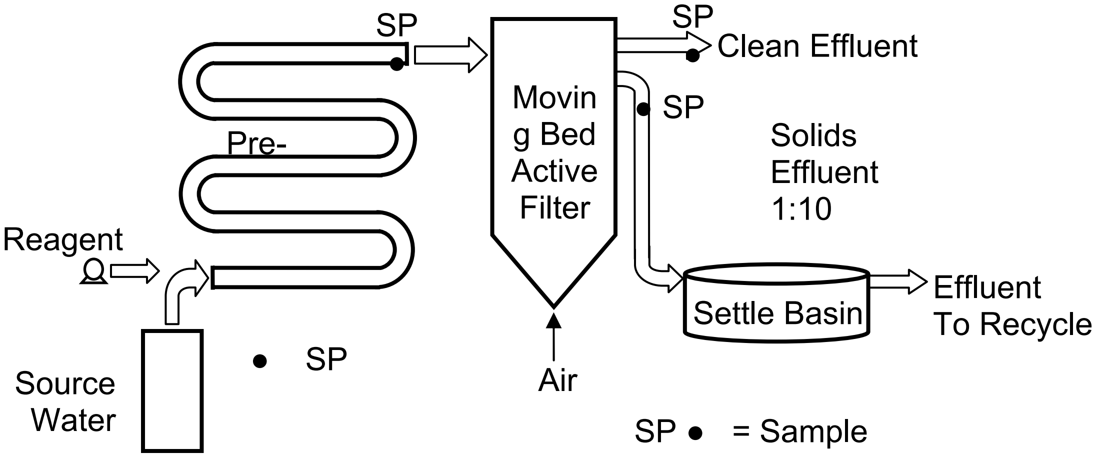


Figure 30. Schematic drawing of the moving bed active filtration process apparatus.

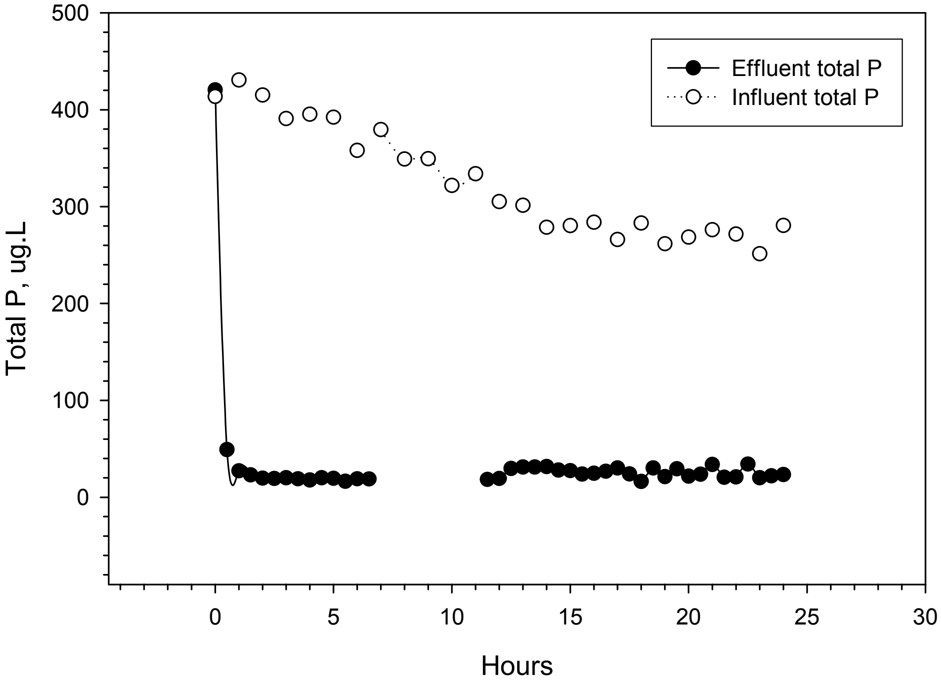


Figure 31. City of Moscow waste water treatment plant discharge. Total reactor influent and effluent total P during a field trial at 10 gpm.

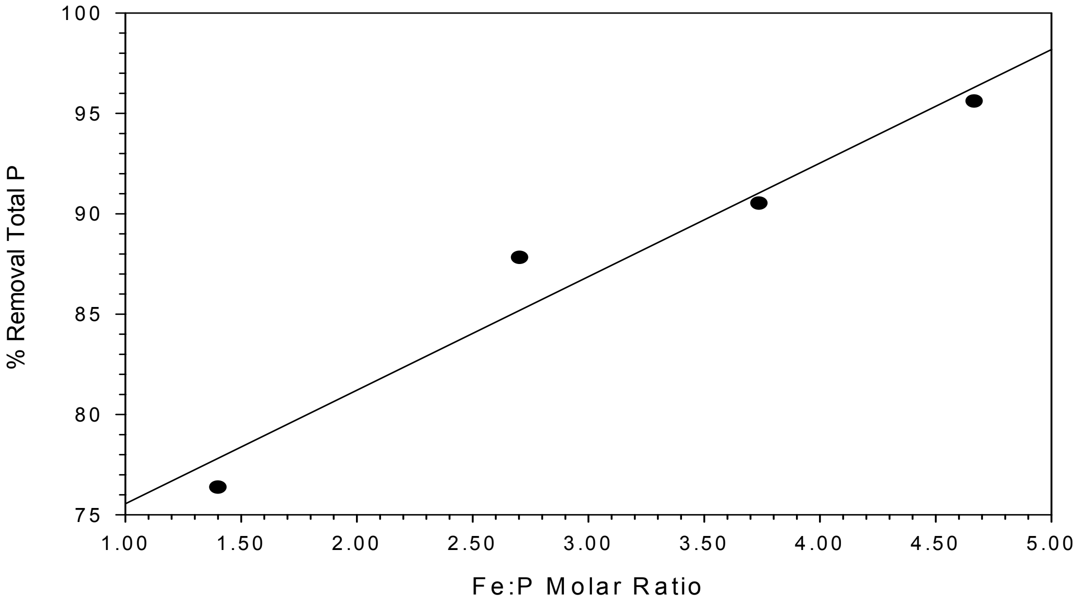


Figure 32. The relationship of total P % removal to Fe:P molar ratio. Experiments conducted at 10-gpm at the City of Moscow, Idaho WWTP.

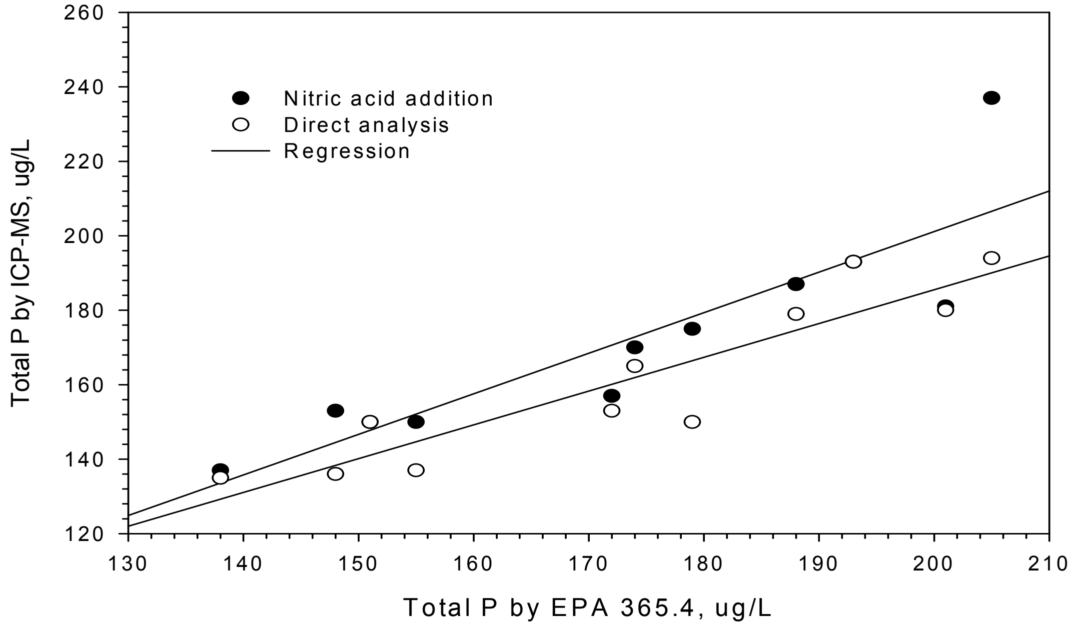


Figure 33. Comparison of total phosphorus results by ICP-MS (with and without nitric acid addition) and EPA Method 365.4.

Figure 34: Experimental flume at Washington State University, Department of Biological Systems Engineering.

Figure 35: Hinged Baffles

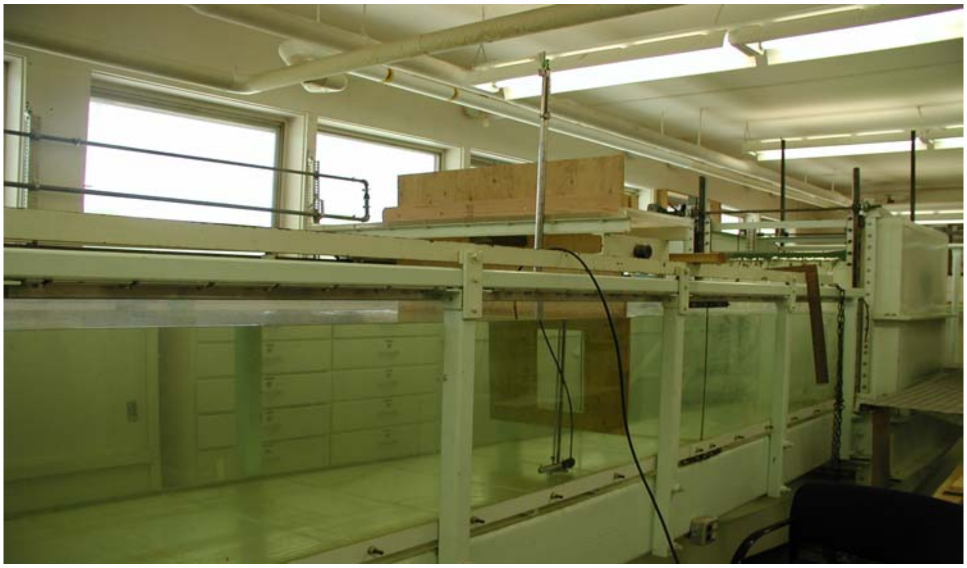


Figure 36: Modified Moving Baffle

Figure 37. Second generation moving baffle prototype during commercial scale field testing in Southern Idaho.

Figure 38: Weir modification testing at commercial scale in Southern Idaho.

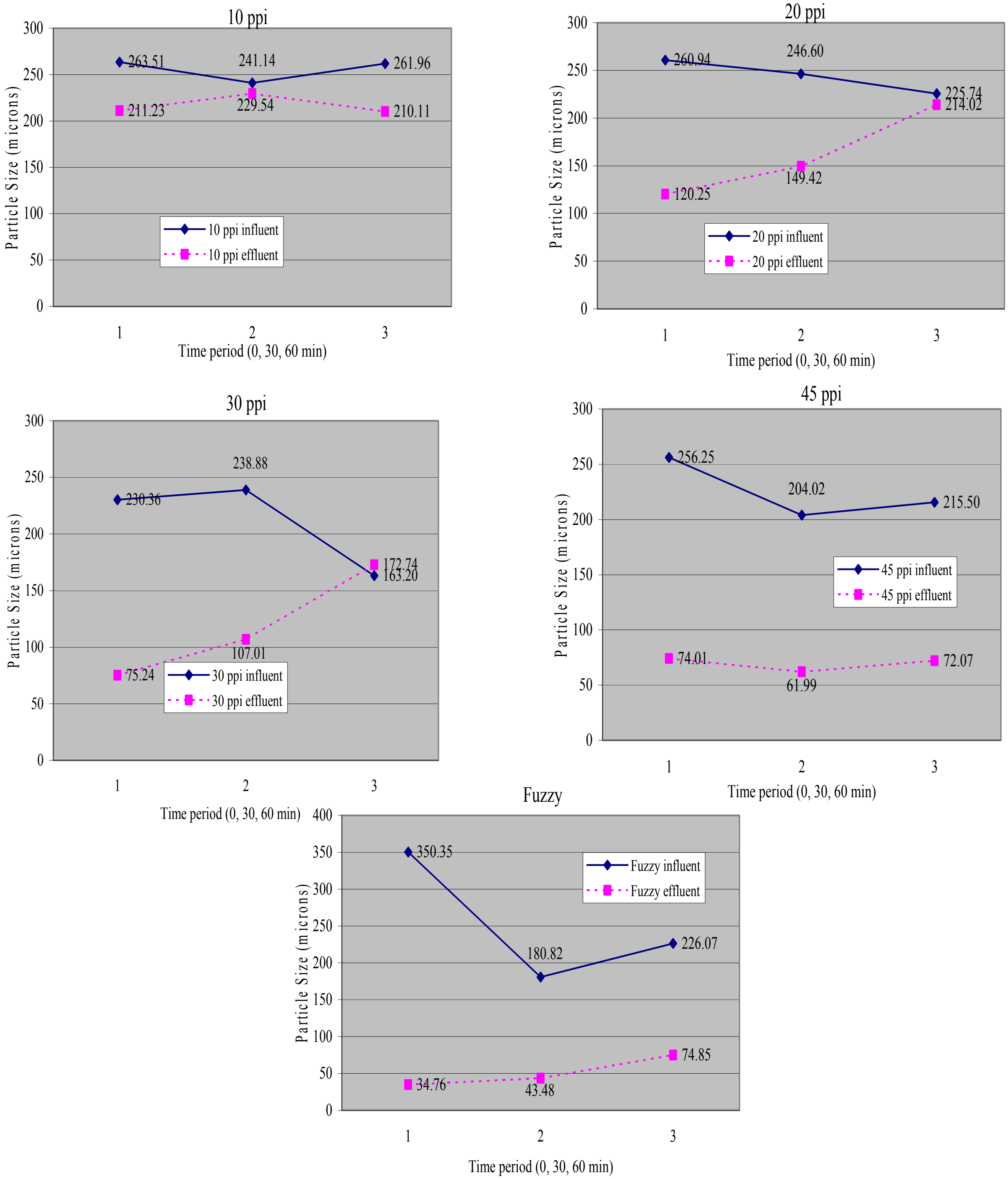


Figure 39: Effluent particle sizes during laboratory testing

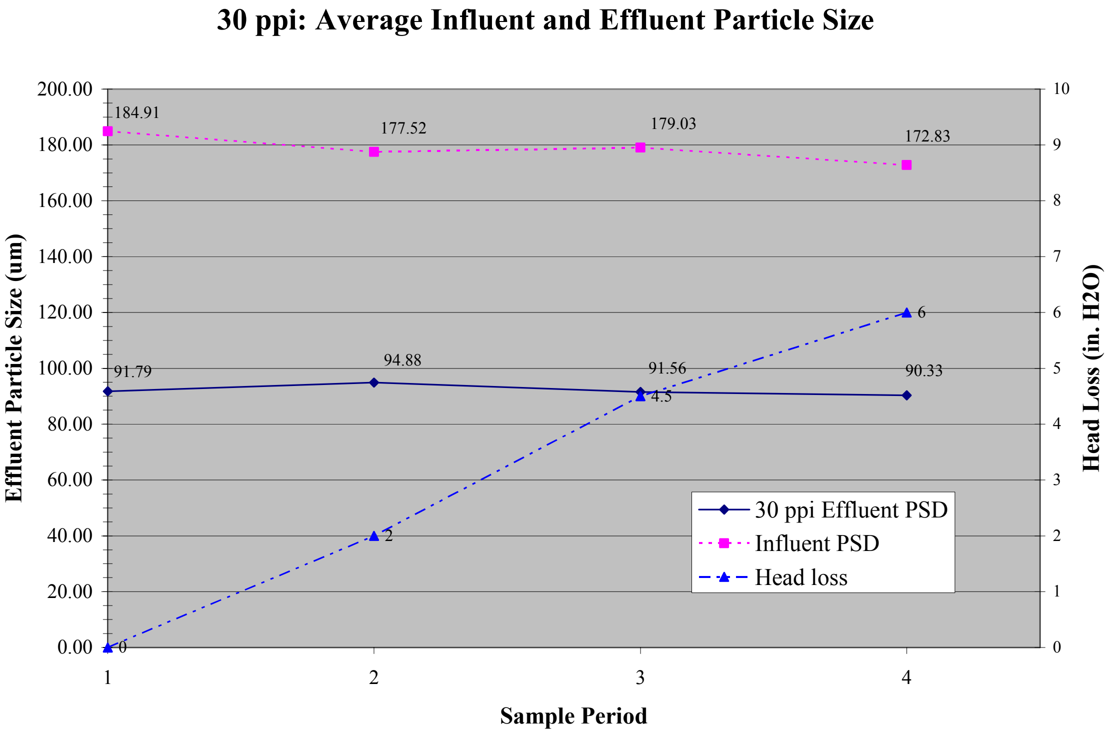


Figure 40: Field test results for 30 ppi reticulated foam for high-rate filtration.

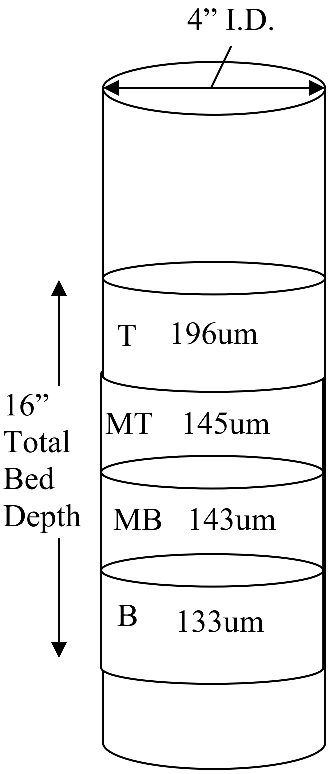


Figure 41: Filter Bed Designations and Median Capture Particle Size

Appendix B:
Tables

Table 1: Facility Characterization

Parameter	Farm				
	1[a]	2	3	4	5
Raceway Flow (L/min)	946	6,000	5,400	10,000	10,200
Farm Flow (10^3 L/min)	5.4	58	192	162	510
Raceway Length (m)	12.1	24.0	39.3	30.5	48.8
Raceway Width (m)	2.1	3.1	4.6	5.5	5.5
Raceway Depth (m)	0.6	0.9	0.7	0.8	0.8
Q-zone Length (m)	N/A	5.3	3.0	6.1	6.4
Rearing Volume (m^3)	16.3	63.6	128.0	140.0	224.0
Fish Density (kg/m^3)	38	27	32	51	37
Annual Production Capacity (MT)	N/A	454	1,021	1,089	3,175

a: Farm 1 is a training facility and is not involved in commercial production.

Table 2: Total suspended solids, corresponding total phosphorus and solids phosphorus content

Location	Field Trip	Sieve Size (µm)	TSS (mg/l)	TP (mg/l)	% P by mass (mg P/mg TSS)
Farm 2	1	10	1.07	0.03	2.80
		53	0.85	0.03	3.53
		105	0.43	0.03	6.98
	2	10	1.63	0.03	1.84
		53	0.91	0.02	2.20
		105	0.63	0.02	3.17
Average(S.D.)		10	1.35(.40)	0.03(0)	2.32(.68)
		53	0.88(.04)	0.03(.01)	2.86(.94)
		105	0.53(.14)	0.03(.01)	5.08(2.69)
Farm 4	1	10	2.35	0.09	3.83
		53	1.38	0.09	6.52
		105	1.13	0.04	3.54
	2	10	2.65	0.05	1.89
		53	2.2	0.05	2.27
		105	1.84	0.04	2.17
Average(S.D.)		10	2.5(.21)	0.07(.03)	2.86(1.37)
		53	1.79(.58)	0.07(.03)	4.4(3.00)
		105	1.49(.50)	0.04(0)	2.86(.97)

Table 3. Characteristics of the six particle groups considered in the simulations (after Wong and Piedrahita, 2000) and sediment transport results for the original raceway system. All terms are as defined in the text.

Particle Group No	*Mass Fraction*	*Settling velocity (cm/s)*	*Particle Size (µm)*	*RSE (g/d)*	*RSA (g/d)*	*TSI (Eq.2) (g/d)*	*PSR*	*PSNR*
1	0.240	3.91	692	0	3,247	3,247	100.0	0.0
2	0.251	2.31	532	0	3,396	3,396	100.0	0.0
3	0.250	1.00	350	1.2	3,483	3,484	100.0	0.0
4	0.136	0.34	204	819	1,007	1,840	54.7	45.3
5	0.117	0.03	61	1,569	14	1,583	0.9	99.1
6	0.006	0.01	35	81	0	81	0.1	99.9
Total				2,485	11,167	13,631	81.8	18.2

Table 4. Simulated solids settling effectiveness (PSR values) in modified raceways as described in Figure 8.

Particle Group No	*Alt. 1*	*Alt. 2*	*Alt. 3*	*Alt. 4*	*Alt. 5*	*Alt. 6*
1	100.0	100.0	100.0	100.0	100.0	100.0
2	100.0	100.0	100.0	100.0	100.0	100.0
3	99.5	99.6	98.6	99.4	97.9	97.4
4	70.2	61.9	64.9	73.8	80.7	77.8
5	7.5	4.4	13.4	11.3	53.0	50.7
6	2.2	1.1	20.2	3.7	49.3	47.6
Total	84.5	83.1	81.0	85.4	91.1	90.3

Table 5: Q-zone Size Analysis

Q-zone Size Analysis

Water Constants (at 15C)	
Water Density (kg/m3)	999.1
Particle Density (kg/m3)	1150
Dynamic Viscosity (N*s/m2)	0.001139
Gravitational Constant (m/s)	9.81

Site 2

Raceway Flowrate (ft3/s, m3/s, l/min)	3.3	0.093	5607
Raceway Width (ft, m)	10	3.048	
TSS Discharge (mg/l), Corresponding Frequency (%) from PSD	1.63	63	
Median Effl. Particle Size (µm)		246.1	
Current Solids P content (%), Discharge (mg/l)	1.93	0.03	

Site 3

Raceway Flowrate (ft3/s, m3/s, l/min)	3.09	0.087	5250
Raceway Width (ft, m)	15	4.572	
TSS Discharge (mg/l), Corresponding Frequency (%) from PSD	2.65	76	
Median Effl. Particle Size (µm)		214	
Current Solids P content (%), Discharge (mg/l)	1.88	0.05	

Q-zone Length (m)	Overflow Rate (m/s)	Captured Stokes Diameter (µm)	Cumm. Freq.	TSS (mg/l)	P (mg/l)	% Change P Discharge
1	0.0307	651.62	98	2.20	0.042	35
2	0.0153	460.76	91	2.09	0.040	28
3	0.0102	376.21	83	1.96	0.038	20
4	0.0077	325.81	76	1.84	0.036	13
5	0.0061	291.41	72	1.78	0.034	9
6	0.0051	266.02	65	1.66	0.032	2
7	0.0044	246.29	61	1.60	0.031	-2
8	0.0038	230.38	58	1.55	0.030	-5
9	0.0034	217.21	55	1.50	0.029	-8
10	0.0031	206.06	52	1.45	0.028	-11
11	0.0028	196.47	48	1.39	0.027	-15
12	0.0026	188.11	46	1.35	0.026	-17

Q-zone Length (m)	Overflow Rate (m/s)	Captured Stokes Diameter (µm)	Cumm. Freq.	TSS (mg/l)	P (mg/l)	% Change P Discharge
1	0.0191	514.84	98	3.23	0.061	22
2	0.0096	364.04	93	3.10	0.058	17
3	0.0064	297.24	87	2.94	0.055	11
4	0.0048	257.42	82	2.81	0.053	6
5	0.0038	230.24	80	2.76	0.052	4
6	0.0032	210.18	76	2.65	0.050	0
7	0.0027	194.59	73	2.57	0.048	-3
8	0.0024	182.02	71	2.52	0.047	-5
9	0.0021	171.61	68	2.44	0.046	-8
10	0.0019	162.81	66	2.39	0.045	-10
11	0.0017	155.23	64	2.33	0.044	-12
12	0.0016	148.62	63	2.31	0.043	-13

Site 4

Raceway Flowrate (ft3/s, m3/s, l/min)	5.9	0.167	10024
Raceway Width (ft, m)	18	5.4864	
TSS Discharge (mg/l), Corresponding Frequency (%) from PSD	2.34	68	
Median Effl. Particle Size (µm)		254	
Current Solids P content (%), Discharge (mg/l)	2.03	0.05	

Site 5

Raceway Flowrate (ft3/s, m3/s, l/min)	6	0.170	10194
Raceway Width (ft, m)	18	5.4864	
TSS Discharge (mg/l), Corresponding Frequency (%) from PSD	2.5	74	
Median Effl. Particle Size (µm)		220	
Current Solids P content (%), Discharge (mg/l)	2	0.05	

Q-zone Length (m)	Overflow Rate (m/s)	Captured Stokes Diameter (µm)	Cumm. Freq.	TSS (mg/l)	P (mg/l)	% Change P Discharge
1	0.0305	649.42	99	3.07	0.062	31
2	0.0152	459.21	92	2.90	0.059	24
3	0.0102	374.94	86	2.76	0.056	18
4	0.0076	324.71	81	2.64	0.054	13
5	0.0061	290.43	76	2.53	0.051	8
6	0.0051	265.12	71	2.41	0.049	3
7	0.0044	245.46	67	2.32	0.047	-1
8	0.0038	229.60	63	2.22	0.045	-5
9	0.0034	216.47	61	2.18	0.044	-7
10	0.0030	205.36	57	2.08	0.042	-11
11	0.0028	195.81	55	2.04	0.041	-13
12	0.0025	187.47	53	1.99	0.040	-15

Q-zone Length (m)	Overflow Rate (m/s)	Captured Stokes Diameter (µm)	Cumm. Freq.	TSS (mg/l)	P (mg/l)	% Change P Discharge
1	0.0310	654.90	100	3.15	0.063	26
2	0.0155	463.08	96	3.05	0.061	22
3	0.0103	378.11	92	2.95	0.059	18
4	0.0077	327.45	88	2.85	0.057	14
5	0.0062	292.88	84	2.75	0.055	10
6	0.0052	267.36	81	2.68	0.054	7
7	0.0044	247.53	79	2.63	0.053	5
8	0.0039	231.54	76	2.55	0.051	2
9	0.0034	218.30	73	2.48	0.050	-1
10	0.0031	207.10	71	2.43	0.049	-3
11	0.0028	197.46	70	2.40	0.048	-4
12	0.0026	189.05	68	2.35	0.047	-6

Table 6. Guaranteed analysis of the 7/32" (5.6 mm) floating trout diet used throughout the phosphorus leaching trials. Diet was manufactured by the Star Milling Company of Perris, CA and sold under the Ace Hi Feeds brand name.

Component		**Inclusion Level**
Crude Protein	minimum	35.30 %
Crude Fat	minimum	5.70 %
Crude Fiber	maximum	3.50 %
Ash	maximum	7.20 %
Phosphorus	minimum	0.81 %
Sodium	maximum	0.47 %
Calcium	minimum	0.77 %
Calcium	maximum	0.94 %

Table 7. Water quality characteristics between March and December 2002 in the 3,300-L semi-closed recirculating trout culture system at the Environmental Research Lab.

Parameter	**Minimum**	**Maximum**	**Mean**	**SEM**
pH	7.12	8.27	7.34	0.134
Dissolved Oxygen (mg/L)	5.25	8.88	7.01	0.406
Temperature (°C)	13.0	21.0	15.9	0.87
Ammonia-Nitrogen (mg/L)	0.04	0.49	0.14	0.040
Nitrite-Nitrogen (mg/L)	0.018	0.560	0.145	0.0530
Nitrate-Nitrogen (mg/L)	2.7	9.8	4.7	0.59
Alkalinity (mg/L)	119	170	141	4.6
In-Flow (L/min.)	0.80	1.38	1.01	0.098

Table 8a. Mean (± SEM) leaching rates of total and reactive phosphorus as effected by water velocities corresponded to a settling basin (0.027 m/s), normal raceway flow (0.079 m/s) and raceway flushing (0.134 m/s).

	Leaching Rate (mg PO_4/hr/g feces)	
Water Velocity	**Reactive***	**Total***
settling basin	1.93 ± 0.792	3.02 ± 2.013
normal raceway flow	1.79 ± 0.641	5.43 ± 1.629
raceway flushing	0.94 ± 0.914	4.54 ± 2.325

*Differences in leaching rates within a column are not significantly different (p>0.05, from a two-way AVONA) for either reactive or total phosphorus.

Table 8b. Mean (± SEM) leaching rates of total and reactive phosphorus as effected by two experimental temperatures, chosen to bracket the common range of water temperatures observed on commercial trout farms in the western United States.

	Leaching Rate (mg PO_4/hr/g feces)	
Water Temperature	**Reactive**	**Total**
low (14.0 ± 0.36 °C)	0.96 ± 0.581^{A}	4.54 ± 1.477^{A}
high (19.3 ± 1.05 °C)	2.88 ± 0.704^{B}	4.43 ± 1.789^{A}

Differences in superscripts within a column indicate a significantly different (p>0.05, from a two-way AVONA) leaching rate.

Table 9. Water Chemistry Report (Hydrochem, 1997)

Ion	Inflow Mg/L	Inflow meq/L	Flume Mg/L	Flume meq/L
Na:	98.0	4.26	104.0	4.52
K:	15.0	0.38	16.0	0.41
Ca:	31.0	1.55	32.4	1.62
Mg:	13.0	1.07	14.4	1.18
Cl:	73.0	2.06	76.0	2.14
HCO3:	156.0	2.56	156.0	2.56
CO3:	0.0	0.00	0.0	0.00
SO4:	30.0	0.62	30.0	0.62
Fe:	0.3	0.01	1.3	0.05
Al:	0.1	0.02	0.1	0.01
Mn:	0.0	0.00	0.0	0.00
NO3:	12.0	0.19	12.0	0.19
Total Dissolved Solids	428.4 Mg/L		442.2 Mg/L	
Ion Balance (Cations/Anions)		1.3		1.4

Table 10. Average performance of the moving bed active filtration process during a 24-hr trial at the City of Moscow, waste water treatment plant.

	Inlet	**Outlet**	**Change**
Total Phosphorus (μg/L)	320 ± 50	24 ± 5	92.6% removal
pH	8.1	6.7	1.4 pH units
Transmissivity (254nm)	75%	84%	9% increase
Turbidity (NTU)	1.3	0.5	62% decrease

Table 11. Results in US$ from conservative engineering economic analysis for three design flows.

Treatment Size	Very Small	Small	Large
Flow rates			
Design flow rate (L/day)	220,000	1.9×10^6	6.8×10^6
Design flow rate (MGD)	0.058	0.5	1.8
Average flow rate (L/day)	57,000	640,000	2.6×10^6
Average flow rate (MGD)	0.015	0.170	0.7
Treatment Costs[a]			
Capital investment (CI)	$69,800	$202,500	$940,400
Annual CI per 3,800 L (1,000 gal)[b]	$1.20	$0.31	$0.35
Operation and Maintenance (O&M)[c]	$2,200	$6,200	$17,400
O&M per 3,800 L (1,000 gal)	$0.40	$0.10	$0.07
Waste Disposal Costs[d]			
CI	$9,900	$28,200	$79,500
Annual CI per 3,800 L (1,000 gal)	$0.04	$0.01	$0.01
O&M	$2,900	$8,200	$10,700
O&M per 3,800 L (1,000 gal)	$0.14	$0.04	$0.02
Total per 3,800 L (1,000 gal)[e]	$1.79	$0.47	$0.44

[a] Treatment capital investment was estimated by scaling the size of the equipment used in this study to the design flow rates conserving the hydraulic loading rate on the filter. Cost is estimated for process costs, then modified, according to a method developed by the U.S. EPA, to include construction and engineering costs (U.S. EPA et al. 2000).

[b] Annual costs assume a 20 yr design life, 7% annual interest rate (U.S. EPA et al. 2000), and use the average flow to calculate the cost per 3,800 L (1,000 gal).

[c] O&M includes replacement sand, ferric chloride, labor, and power.

[d] Waste disposal capital and O&M costs are one-fifth the U.S. EPA estimation of waste disposal costs for coagulation assisted microfiltration, which assumes 25 mg/L $FeCl_3$ addition, producing more waste (U.S. EPA et al. 2000).

[e] Total annual cost includes annual treatment CI and O&M, annual waste disposal CI and O&M.

Table 12. The effect of diet on fecal density determined using a horizontal distribution tank.

	Section		
Diet	1*	2*	3*
11, Control	7.4^{b}	33.9^{a}	57.6^{b}
12, Poultry oil	10.7^{a}	37.2^{a}	51.4^{c}
13, Tallow	4.5^{b}	33.3^{a}	62.1^{b}
14, Superbind	6.4^{b}	24.0^{b}	69.4^{a}
P>F value	.01	.01	.01
R^2	.78	.79	.91
C.V.	55.56	21.39	10.36

*% of total fecal load per day

Table 13: Captured Solids and the Effects on Phosphorus Discharge

Influent TSS (mg/l)	1.5	
Hydraulic Loading (lpm, gpm/ft2)	24	75
Run Time (16 hr)	16	
Percent P in TSS	2	

Location in Filter Bed	ID	Captured Particle Size (um)	Crucible ID	Initial Weight	Final Weight	Filtered Sample	TSS (mg/l)	Total Captured Material (mg back calculated to 16l wash water)
Top	T	196	36	1.094	1.1347	100	407	6512
Middle Top	MT	145	2	1.0918	1.1045	100	127	2032
Middle Bottom	MB	143	45	1.084	1.0908	150	68	1088
Bottom	B	133	10	1.0994	1.1071	200	77	1232

10864	Total mass intercepted solids (mg)
34560	Estimated Total Solids Load (mg)
31%	Percent Intercepted Solids (% total)
31%	Percent Reduction in P Discharge (% total)