

Five-year Changes in Pond Sediment Nutrients and Phosphorus Adsorption-Desorption at Minor Clark Fish Hatchery, Kentucky

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Abstract: Earthen hatchery pond sediments may provide additional nutrients to the water column and act as a sink for nutrients and excess fertilizer. In 2008 and again in 2013 soil nutrient concentrations and phosphorus (P) adsorption were examined in five earthen ponds at Minor Clark Fish Hatchery, Kentucky. These ponds are annually filled with oligotrophic water from an upstream reservoir, fertilized, and drained during normal hatchery operations. Over time, pond nitrogen (N) and P additions have not kept up with soil losses. Soil extractable P concentrations decreased about an order of magnitude between 2008 and 2013. Soil %N decreased by nearly 50% over the same time period. Other soil nutrients (organic carbon, calcium, and manganese) remained the same. Soil collected in 2008 desorbed P under normal fish rearing water quality conditions. Using higher isotherm P-concentrations on 2013 soils, more P was adsorbed as incubation concentrations increased, with greatest adsorption occurring at the highest loading ($1500 \mu\text{g P L}^{-1}$). Phosphorus adsorption was correlated with concentrations of extractable aluminum and % clay, but not with extractable iron. Soils collected in 2013 incubated with unspiked reservoir water still desorbed P to the water, but at a rate an order of magnitude lower than 2008 soils. The ability of soils to release P to the water under normal conditions has decreased over time, as pond soils exhausted their extractable and labile P supplies. Regular annual flooding and flushing with low ionic strength water has resulted in P depletion in Minor Clark Fish Hatchery pond soils. Given the relatively low contribution of sediments to pond P budgets during fish rearing, lining ponds could be a worthwhile management strategy.

Key words: fertilization, biogeochemistry, soil, nutrient cycling, wetland, fish

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Fertilizer has traditionally been used to increase productivity in fish ponds (Bennett 1962, Piper et al. 1982, Yan and Yao 1989), but years of adding excess nutrients usually result in sediment nutrient accumulation. Because earthen pond soils may contribute nutrients to pond waters, organic or inorganic fertilization can be reduced if the system can maintain adequate fertility internally (Swingle et al. 1963, Masuda and Boyd 1994, Zhou and Boyd 2015). In China, organically fertilized fish pond sediments are “harvested” and recycled to grow crops as part of an ecologically engineered system (Yan and Yao 1989). Earthen fish ponds are considered more desirable than concrete because they provide nutrients, and produce higher quality fish. Hatchery managers often mechanically disc ponds before filling them, in part to increase the soil surface area available to provide nutrients to the water column (Piper et al. 1982).

Hatchery pond fertilization is generally not conducted with an in-depth knowledge of the exact nutrient concentrations in filling waters or measurements of potential internal loading of nutrients by pond sediments. Fertilizer additions may simply be determined by using regular checks of Secchi depth as a proxy for fertility and algal biomass or estimated based upon historical practices. Chemistry of the source water and interactions between source water and pond sediments, may be specific to the particular nutrient budget of source water and sediment origin and history in each hatchery.

It would be useful to know how much sediments contribute to nutrient budgets during fish rearing. Phosphorus (P) is the most important component of primary productivity in freshwater systems (Schindler 1977, 1978; Smith 1979; Hecky and Kilham 1988), and is the key nutrient added to increase primary productivity in hatchery ponds. Phosphorus is also dynamic in productive shallow-water sediments and interstitial water (Mitsch and Gosselink 2015). Under-fertilization can result in reduced fish yields; over-fertilization with P can have multiple negative consequences to fish survival. When P-loading is high, nitrogen (N) is generally becomes the next limiting nutrient in freshwater (Lewis et al. 2011). Over-fertilization with P without keeping the N loading high can create problems because the relative ratio of P to N can determine the algal community structure. Low N:P ratios favor N-fixing “bluegreen algae” (cyanobacteria) which are generally undesirable (Tilman 1977, Smith 1983, Tew et al. 2006, Reeder and Middleton 2009). Over-fertilization can also result in dissolved oxygen depletion and other problems (Hepher 1962, Middleton and Reeder 2003). If P additions create hypereutrophic conditions that result in sediment and water anoxia, additional P may be released from the sediments, perpetuating a lethal positive feedback.

A variety of factors can affect the adsorption or release of available P from sediments (Logan 1982). Richardson (1985) showed that P sorption and release in shallow sediments was attributable

to the concentrations of extractable iron (Fe) and aluminum (Al) in shallow flooded soils. Soil P sequestration is enhanced by clay colloids and Al oxides in clay (Olsen and Watanabe 1957, Logan 1982, Miller et al. 1986, He et al. 1997, Penn and Warren 2009), and by complexing with cations (Cole et al. 1953, Logan 1982). Hatchery ponds are an interesting case, because they may be drained and filled multiple times (alternating between aerobic and anaerobic chemistry) and may receive large additions of organic and inorganic fertilizer. Phosphorus is generally released under anaerobic conditions and can be sequestered by sediments or precipitated out of the water column by cations (e.g., calcium [Ca] and Fe) under aerobic conditions (Patrick and Khalid 1974, Sah and Mikkelsen 1989, Reddy and D'Angelo 1994, Mitsch and Gosselink 2015).

The potential past contribution of sediments to hatchery nutrient budgets becomes more important if ponds are fitted with liners to reduce erosion or seepage losses (Rogge et al. 2003, Ward et al. 2011). At Minor Clark Fish Hatchery (Minor Clark), Kentucky, plastic liners have been added to four ponds, eliminating sediment nutrient contributions or buffering effects on water quality. Saengrungruang and Boyd (2014) found that even permeable geotextile liners reduced sediment P sorption, and suggested that this resulted in greater P water concentrations in lined ponds when compared to earthen ponds (which sequestered nutrients).

There is ample evidence that most fish ponds accumulate nutrients (Boyd 1995, Zhou and Boyd 2015). However, many freshwater fish hatchery studies have been conducted in regions where water alkalinity and nutrient concentrations are much higher than those experienced at Minor Clark (often 2- to >10-fold higher than source water or fertilized waters). This study examined the effects of constant filling and flushing with source water that was relatively infertile, with low ionic strength, on Minor Clark pond sediment nutrient accumulation.

The goal was to assess changes in sediment nutrient concentrations in Minor Clark ponds and determine how these changes might be related to pond sediment characteristics, and the historical flooding, flushing, and fertilizing. One way to determine if some of the fertilizer applied to ponds over time is captured and stored by pond sediments would be to examine if the sediments have more nutrients at a point in time than they did in the past. To assess these changes at Minor Clark, sediment chemistry and nutrient concentrations were measured in 2008 and then again in 2013. To specifically address P dynamics, the ability of the soil to bind phosphate ions from the water (ion adsorption) can be evaluated under different conditions using P adsorption isotherms. Soil's capacity to adsorb P varies depending upon the nature and physiochemistry of the soil colloids, and overlying water's P con-

centrations. To further clarify why Minor Clark Fish Hatchery pond sediments might be a source or sink of P under different fertilizer loadings, P isotherms were performed by incubating sediment samples in water with P concentrations normally encountered during fish rearing. Because adsorption isotherms normally evaluate soil sorption capacity using higher concentrations than found in normal field conditions at Minor Clark, additional soil isotherms were conducted at much higher P concentrations than the ponds experience during fish rearing. Adsorption-desorption characteristics under different P loading scenarios can help determine if low-nutrient source water was affecting sediment bioavailable P retention or release.

Methods

Study Site

Minor Clark is located at the base of Cave Run Lake Dam, in Rowan County, Kentucky (38.116802N, 83.548185W). The hatchery was built in 1973 on Licking River floodplain sediments. Minor Clark ponds are fed by relatively oligotrophic Cave Run Lake water (Davis and Reeder 2001), and the water inlet system allows managers to take water from different lake levels to regulate temperature. Minor Clark has 82 0.4-ha surface area ponds. These ponds were built with sloped bottoms: deep ends are kept about 1.5 m depth; whereas the shallow end is slightly less than 1 m deep. When ponds are filled and rearing fish, pond-waters are usually aerated if anoxic conditions are noted or anticipated. In 2008 aeration was accomplished using tractor-driven paddle wheels. Since 2009, ponds have been aerated electrically using floating regenerative blower systems. Ponds are generally drained overwinter.

Soil Sample Collection

The ponds chosen for this study were picked randomly in 2008 as part of a college Ecology class laboratory activity. A running average (performance curve) showed samples from five ponds were adequate to obtain a mean concentration for the population. These five ponds were sampled again in 2013 using the same methods. Sediment samples were taken from three locations in each pond: near the middle, and in the deep and shallow sections. Individual samples were a mixture of six soil probe samples (about 10 cm deep): these six were taken in a star pattern from a point around a random site (chosen by throwing the probe over the shoulder). The six samples from each point were mixed together on paper. Samples were placed in paper soil sample bags, and allowed to air dry before being sent to the University of Kentucky (UK) soil lab for analyses (pH, extractable P, Ca, and manganese [Mg], %N, % organic carbon [C]). The UK soil lab used Malich 3 as an extracting agent for determining bioavailable nutrient concentrations. In

2008, extractable Fe, Al, and soil texture were not measured. After observing the results of the 2008 P adsorption experiments, these analyses were added for 2013 collected soils.

Phosphorus Adsorption-Desorption Measurement

Isotherm analysis requires thoroughly mixing a soil sample with water solution containing known P concentrations. After mixing, the resulting slurry is filtered or centrifuged to remove the soil, and the solution's P concentration measured to determine how much P was adsorbed by the soil. If the solution has more P than before mixing with the soil, adsorption is negative (desorbed). Because of their physical and chemical structure, soils usually have a high affinity for binding phosphate. In general, soils with many available physical or chemical anion binding-sites will adsorb most of the phosphate available in a solution. As the water P concentrations increase, soil adsorption increases until the point that no further sites are available to bind the phosphate anion (McBride 1994).

Phosphorus adsorption isotherms of soil samples were run in triplicate for each pond (deep, middle, and shallow zones). One g of well-mixed soil was placed in 25 ml of solution in a 50-ml Nalgene round bottom incubation tube (soil to solution ratio of 1:25 with 50% head space). The slurry was placed in an end-over-end spinner (about 6 rpm) for 24 h at 24–26 °C (following the recommendations of Barrow and Shaw [1979]). The solution was then filtered through a 0.45- μm glass fiber filter (Wathman GF/A), and filtered water soluble reactive P (SRP) was measured using the ascorbic acid method (Murphy and Riley 1962). The difference in the quantity of phosphate present before and after shaking in the equilibrium solution was used to calculate P adsorption ($\mu\text{g P g}^{-1}$ soil).

Because this study was concerned with how the soil responded to specific real-world conditions, P adsorption isotherm incubations were varied from standard protocols (outlined in Nair et al. 1984). Electrolyte concentration can change P adsorption-desorption characteristics (Ryden et al. 1977, Barrow et al. 1980);

therefore, as medium for soil incubation, unsterilized Cave Run Lake water was used (conductivity $<180 \mu\text{S cm}^{-1}$, alkalinity $<20 \text{ mg CaCO}_3 \text{ L}^{-1}$, SRP $<10 \mu\text{g L}^{-1}$, inorganic N $<400 \mu\text{g L}^{-1}$) rather than sterile distilled water or sterile artificially buffered water (such as $0.01 \text{ mol L}^{-1} \text{ CaCl}_2$ electrolyte). In 2008 these incubations were run at relatively low equilibrium solution concentrations (0, 3, 7, 33, and $65 \mu\text{g L}^{-1}$ P) to simulate P concentrations typically found in fertilized pond waters during fish rearing ($<70 \text{ mg L}^{-1}$, Reeder and Middleton 2009). In 2013, higher concentrations were used in equilibrium solutions to determine if sorption-desorption would vary with more intense fertilization scenarios (8, 96, 150, and $1500 \mu\text{g P L}^{-1}$).

Data Analyses

Student's *t*-tests were used with an alpha level of 0.05 to assess differences in mean soil nutrient concentrations between the two years. Differences between mean P-adsorption across different concentrations were compared with ANOVA using a Fisher's Least Significant Difference test for significance. Correlations were used to compare maximum P-adsorption to soil characteristics (extractable Fe, extractable Al, and % clay). Statistical significance of the correlation value was determined using Fisher's *r* to *z* with a 95% confidence limit. All statistics were calculated using Statview 4.0 for Macintosh (Abacus Concepts 1992).

Results

Changes in Sediment Conditions between 2008 and 2013

Pond soils were mostly classified as loams with relatively strong cation concentrations dominated by Ca. For most of the measured parameters, soil conditions were relatively stable over time (Table 1). Soil organic matter and nitrogen were present in the normal range for Kentucky bottomland alluvial soils. Mean soil pH was similar between 2008 and 2013 (Student's *t*-test, $n = 10$, $P = 0.15$). Major cations also did not show any changes in mean concentrations between

Table 1. Soil characteristics in Minor Clark fish hatchery ponds in 2008 and 2013. Concentrations of phosphorus (P), calcium (Ca), manganese (Mg), aluminum (Al), and iron (Fe) are given in mg kg^{-1} . The latter two were only measured in 2013, as was textural class composition.

Pond	P		% N		% C		Ca		Mg		Al	Fe	Textural class		
	2008	2013	2008	2013	2008	2013	2008	2013	2008	2013	2013	2013	% sand	% silt	% clay
													2013	2013	2013
6	52	3.2	0.23	0.10	1.6	1.2	1378	1259	141	150	579	461	36	46	19
8	39	3.0	0.14	0.07	1.0	0.7	1071	1162	131	164	692	334	28	51	21
46	26	3.0	0.12	0.06	1.6	1.2	716	721	116	144	572	387	51	35	15
57	43	3.2	0.19	0.09	2.1	1.4	1186	1152	135	109	470	429	56	32	13
58	24	3.1	0.16	0.10	1.5	2.0	824	1131	113	167	590	363	47	37	17
Mean	37	3.1	0.17	0.08	1.6	1.3	1035	1085	127	147	581	395	43	40	17
SE	16	1.4	0.08	0.04	0.7	0.6	463	485	57	66	260	177	19	18	8

years (Table 1). Mean extractable concentrations of Ca and Mg were 5% and 15% higher, respectively, but these changes were not significant (Student's *t*-test, *df*=8, *P*=0.75 and *P*=0.13, respectively). Mean percent organic C was 16% lower in the 2013, but again this change was not significant (Student's *t*-test, *df*=8, *P*=0.39).

Two critical soil macronutrient concentrations were lower in 2013 than in 2008 (Table 1). Mean soil %N was reduced by about half (Student's *t*-test, *df*=8, *P*=0.004). Soil extractable P concentrations were lower than normally observed in rich bottomland soils during both years. Mean extractable P concentrations decreased an order of magnitude between years (Student's *t*-test, *df*=8, *P*=0.0002). Extractable Al and Fe concentrations in 2013 were similar to other Kentucky bottomland alluvial soils (Table 1).

Soil P Adsorption-Desorption Measurements

Soil samples from 2008 released P at the same mean rate (~5 $\mu\text{g P g}^{-1}$) in all incubation concentrations (Table 2, ANOVA, Fisher's LSD >0.05 for all pairs). Like in 2008, soils collected in 2013 incubated in the lowest concentrations (8 $\mu\text{g P L}^{-1}$) desorbed P but at a rate about an order of magnitude less than soils collected five years before. Soils from 2013 incubated at higher P concentrations than used in 2008 adsorbed P. In 2008, soils mixed in 65 $\mu\text{g P L}^{-1}$ released P to the water; however, at similar concentrations (96 $\mu\text{g P L}^{-1}$), 2013 soils adsorbed P. Adsorption capacity of soils collected in 2013 incubated at higher P concentrations increased with incubation solution P-concentrations.

Soil adsorption in the 1500- $\mu\text{g P L}^{-1}$ solution was correlated with extractable Al ($r=0.724$, $P=0.003$) and % clay ($r=0.734$, $P=0.002$), but not to extractable Fe ($r=-0.400$, $P=0.143$). Other soil variables (Ca, Mg, and pH) were not correlated with maximum P adsorption

Table 2. Soil P-adsorption isotherms for Minor Clark Fish Hatchery ponds at various water P concentrations ($\mu\text{g L}^{-1}$) in 2008 and 2013.

Pond	2008				2013			
	0	7	33	65	8	96	160	1500
6	-0.4	-4.4	-5.7	-5.3	-0.4	1.1	3.8	37.0
8	-2.6	-2.5	-3.5	-3.4	-0.2	1.6	3.7	38.0
46	-1.8	-1.8	-3.4	-3.6	-0.5	1.4	3.7	36.0
57	-5.6	-6.5	-6.7	-7.4	-0.8	0.4	2.6	33.0
58	-4.6	-6.0	-6.2	-6.5	-0.5	1.2	3.5	35.0
Mean	-3.0	-4.3	-5.1	-5.2	-0.5	1.1	3.5	36.0
SE	0.9	2.1	1.6	1.8	0.1	0.5	0.5	2.0

Discussion

Loss of Soil Nutrients Over Time

Hatchery ponds are generally dependent upon external addition of nutrients (fertilization) to create primary production sufficient to grow fish. Decades of pond fertilization should result in high pond sediment nutrient concentrations. This study found that nutrient concentrations in sediments from ponds filled with low ionic strength, low nutrient source water lost nutrients between a 5-year period, despite annual organic and inorganic fertilizer additions. Managers in ponds with low nutrient, low alkalinity source water may find that more fertilization is required over time to maintain production, as sediments lose their ability to contribute to the water column nutrient budget.

Loss of sediment P is usually the result of "internal loading" which happens in eutrophic systems when anaerobic sediments release P (Mitsch and Gosselink 2015). Excess P should never be added to a hatchery ponds in concentrations that would create this potentially deadly feedback on pond dissolved oxygen and P-concentrations. Hatchery managers endeavor to keep water column DO concentrations high which creates high-redox aerobic conditions that should result in sediment P accumulation, not loss. Accumulation of sediment nutrients over time could be desirable to hatchery managers since nutrient-rich pond sediments can provide some N and P by dissolution which can reduce the need for fertilizer (Saengrungruang, and Boyd 2014, Zhou and Boyd 2015).

Continually filling and draining Minor Clark ponds with low ionic content water reduced P and N concentrations without altering concentrations of other major soil cations (Ca and Mg), without causing changes in soil pH, and without accumulating organic C. This contrasts to most studies of hatchery and wetland soils where C, N, and P are sequestered in soils and sediments (Boyd and Munsiri 1996, D'Angelo 2005, Mitsch and Gosselink 2015, Zhou and Boyd 2015). The loss of P over time was most dramatic in the present study, with soil P concentrations decreasing an order of magnitude over just five years. Fertilization was not sufficient to replace soil N and P losses. Phosphorus losses can be explained by examining the soil adsorption data. The 2008 soils had higher P than in 2013, allowing greater losses of labile P from the soil to the water. As the labile pool of P in the soil was "mined" by the overlying water over time, reduced P stocks decreased the ability of the soils to desorb P.

Minor Clark pond soils desorbed P when incubated in concentrations where most soils adsorb almost all the available P (Nair et al. 1984, Sah and Mikkelsen 1989, Reddy and D'Angelo 1994) including soils in other hatcheries (Masuda and Boyd 1994, Boyd and Munsiri 1996, Tepe and Boyd 2002, Zhou and Boyd 2015). Nitrogen losses from aerobic sediments can be expected, but labile P

tends to bind tightly with various soil components (Stumm and Morgan 1996, Mitsch and Gosselink 2015).

Potential Soil Characteristics Determining P Sediment-Water Dynamics

The 2008 P sorption experiments were probably run at too low of concentrations and too little range to gain information about P soil adsorption dynamics. The P-depleted sediments absorbed P at concentrations similar to when P was released in 2008, suggesting that more P adsorption sites are available, as labile P was removed from sediments over time. Unlike most studies, Minor Clark soils were a source of P, rather than a sink of P at regularly utilized isotherm solution P concentrations. This is probably realistic in terms of what conditions are occurring over Minor Clark pond sediments during filling and fish rearing. The loss of available P over time supports this theory. Comparisons of sorption between 2008 and 2013 showed that as the soils have lost available P, their ability to act as a P source decreased about an order of magnitude. The sediment P was removed as fish were harvested, or as dissolved P and plankton flushed out when the ponds were drained.

Adsorption at high P concentrations in the 2013 soils demonstrates that Minor Clark pond soils had ample available sites to sorb and adsorb P, but only if loading or ionic concentrations were increased. Minor Clark pond soils had a high cation exchange capability and likely had many potential sites for P sorption. The low P and ionic concentrations in the source water resulted in P release rather than adsorption at water P concentrations normally encountered when rearing fish at Minor Clark (Reeder and Middleton 2009).

Phosphate is generally bound to sediment and will preferentially bind to soil colloids, especially soils high in Al, Fe, and clay (Russell and Low 1954, Olsen and Wantabe 1957, Logan 1982, Richardson 1985, Miller et al. 1986, He et al. 1997, Mitsch and Gosselink 2015). However, adsorption only occurred at high loading rates in Minor Clark pond soils. The highest P adsorption rates observed in this study ($>30 \mu\text{P g}^{-1}$) were greater than those reported in many other studies. For example, Lefrancois et al. (2010) found a maximum adsorption of 1.32 mg P g^{-1} . Nair et al. (1984) examined various soils from across the United States and measured adsorption of $0.8\text{--}1.0 \mu\text{g P g}^{-1}$ in clay and silt loams incubated at $0\text{--}6.45 \mu\text{mol P}$. They measured adsorption of $1\text{--}8 \mu\text{g P g}^{-1}$ at $16\text{--}323 \mu\text{mol P}$ concentrations. These comparisons support the idea that Minor Clark soils have great capacity to adsorb excess fertilizer. Phosphorus adsorption in Minor Clark soils is most likely facilitated by Al oxides and clay but not Fe. Although low pH can contribute to P release by sediments, pH in Minor Clark ponds was not as acidic as those where pH caused release (Penn and Warren 2009).

The release of P by shallow productive anaerobic soils is well

understood, and mostly determined by dynamics with P bound to Fe and sediment redox (Richardson 1985, Stumm and Morgan 1996, Mitsch and Gosselink 2015). The capacity to release P in Minor Clark pond sediments under oxidizing conditions is somewhat unusual. One could expect to observe P removal from the water and sequestration in sediment when managing ponds to keep water aerated (aerobic, high redox conditions) or when combined with available sorption sites and plentiful oxidized Fe in the water and sediment. But Minor Clark's source water has low fertility with no to little P in the water; therefore, there is not much P available to be precipitated out of the water column or sequestered by sediments. Instead, the chemistry of the source water causes Minor Clark pond soils to release P, in the absence of anaerobic conditions, as long as water P concentrations and ionic composition are low.

The P isotherm results in this study were unusual but not unprecedented. Laboratory experiments with various wetland soils by Patrick and Khalid (1974), found a dynamic similar to these observations. In their experiments, P was desorbed in no-P equilibrium solutions (0 mg P L^{-1}), but was adsorbed strongly, mostly to hydrated ferric oxide complexes, in high concentrations of P (100 mg L^{-1}). This effect was seen even in alluvial soils with low native P, similar to the soils in Minor Clark ponds. As expected, soil P release was higher under anaerobic conditions than aerobic, but the mechanism for release still existed in aerobic conditions if native P in the water was low.

Implications for Pond Nutrient Management and Liners

It appears that Minor Clark pond soils have ample capacity to absorb P fertilizer if the concentration gradient is high enough, but when no P is available they become a source. This would seem to provide a buffer system; however, a buffer to absorb excess P is not needed in Minor Clark ponds because managers do not add enough P from organic and inorganic fertilizer during fish rearing to require the soils to adsorb excess nutrients. Minor Clark pond sediments should only act as sinks for P if they are over-fertilized.

As suggested by others (Boyd 1995, Zhou and Boyd 2015), earthen sediments can contribute P and other nutrients to the water column in hatchery ponds, reducing the need for excess fertilizer. Earthen ponds are considered more desirable than impermeable or semipermeable lined ponds because the sediments can act as a buffer and sequester excess nutrients, reducing fluctuations in algal growth cycles (Boyd 1995). If pond sediments can provide sufficient P for fish growth, P-fertilization could be reduced or even eliminated. Lowering water column P concentrations by reducing P-fertilization is not only cost effective but is often beneficial by reducing potentially lethal DO fluctuations (Middleton

and Reeder 2003) and by encouraging the growth of helpful algae (Smith 1983, Tew et al. 2006).

At Minor Clark, and potentially at other hatcheries with low ionic strength water, sediments may have contributed some P to the water column but the contribution of soils to the pond nutrient budget may become less significant over time. This would suggest that at these hatcheries, earthen sediments may not be critical to successful fish rearing and some outside source of P may be needed either as organic or inorganic fertilizer. Primary productivity in low alkalinity waters in the Minor Clark region have been demonstrated to be P-limited (Reeder 2017), but excess P could be contributed by organic fertilizer alone (Reeder and Middleton 2009).

At Minor Clark, seepage water losses from ponds were severe enough to require that some ponds be lined. If pond sediments are an important buffer or nutrient contributor, they could alter fertilization regimes and water additions during fish rearing. The results of this study suggested that Minor Clark and similar hatcheries with pond sediments that are not significant contributors of limiting nutrients could be good candidates for the installation of a lining without causing radical changes to rearing strategies. Lining ponds can have a number of advantages since linings reduce growth of undesirable emergent vegetation, seepage water loss, potential erosion, and loss of fertilizer to the sediment. Earth is probably not necessary in Minor Clark ponds as Minor Clark ponds are not functioning in water with high ionic strength and sediments do not contribute the most important nutrient to the ponds in high concentrations.

Minor Clark has a good record of success rearing fish (Reeder and Middleton 2009) and could benefit from lining ponds. Relatively low additions of P and N have traditionally been required to maintain the fishery, which minimizes the impacts of hypereutrophication or establishment of low N:P ratios created by P release from the sediments. This study suggested that sediments are not an important component of P dynamics in the Minor Clark ponds. Lined ponds could make the effect of fertilizer additions easier to predict since there is no confounding interaction with sediments. Other hatcheries interested in lining ponds to reduce water losses may want to examine the role of sediments to nutrient budgets to determine if fertilization will be sufficient without contributions from sediments. If the hatchery has high-nutrient source water or high P contributions from sediments, nitrogen additions may be more important than P additions to reduce the chance of DO depletion and to reduce blooms of undesirable blue-green algae.

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