Comparison of Liberal and Conservative Water Exchange Effects on Water Quality and Channel Catfish Fingerling Production in Hatchery Ponds

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Management Data Series
No. 265
2011

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ACKNOWLEDGEMENTS

We thank the A. E. Wood, Possum Kingdom, and Dundee state fish hatchery staffs for manpower support, coordination, and close attention to detail that made this across-hatcheries study possible. Support provided by the Texas Parks and Wildlife Department Inland Fisheries Analytical Services Laboratory, especially the processing of chlorophyll samples by Steven Hamby and diagnosis of disease by Greg Southard, is greatly appreciated. This study was funded in part by Federal Aid in Sport Fish Restoration Grants F-95-D, F-96-D, and F-101-D to the Texas Parks and Wildlife Department.

ABSTRACT

We evaluated liberal and conservative water use (treatments) in channel catfish *Ictalurus punctatus* grow-out ponds at three Texas Parks and Wildlife Department fish hatcheries to establish baseline information on water quality and fish production performance, evaluate an existing best management practices (BMP) guideline for the production of 229-mm channel catfish, and determine which water use strategy provides more efficient use of water in plastic-lined ponds. Thirty ponds, 10 at each hatchery consisting of 5 replicate ponds per treatment, were stocked with 90-mm total length fingerlings at a density of 21,570 fish/ha. Catfish were fed a commercial diet to satiation and reared to an average total length of 253 mm in about 90 d. Treatments were implemented 30 d after fish stocking on the same day aeration of all ponds began. Liberal treatment ponds received continuous flow of fresh water at an exchange rate of one pond volume per week or 379 L/min. These ponds also received emergency flushing (757 L/min) when an established criterion (morning DO < 4.0 mg/L or afternoon pH > 9.5) was met. Conservative treatment ponds were treated as individuals and received fresh water (i.e. emergency flushing of 757 L/min) only when either of the established criterion was met. For all ponds emergency flushing was discontinued on the day morning DO was equal to or greater than 4.0 mg/L or afternoon pH fell below 9.5. Water use, water quality, incidence of disease outbreak, and fish production were compared between treatments. The liberal treatment used about 6 times more water and significantly reduced pH by 0.4 and increased DO by 1.1 mg/L compared to the conservative treatment ($P < 0.05$). Water temperature, ammonia concentration, and chlorophyll *a* did not significantly differ between treatments ($P > 0.05$). Disease outbreak occurred in two liberal treatment ponds and one conservative treatment pond but fish mortalities that did not significantly differ between treatments. Except for the feed fed (kg/ha) to fish, none of the fish production variables compared (e.g., survival, growth rate, fish biomass, feed conversion) significantly differed between treatments. Despite the similarity of production performance, fish production efficiency was better for the conservative than for the liberal treatment because the input cost of water was significantly higher for the liberal treatment. Thus, we conclude that the conservative treatment represents the more efficient use of water in plastic-lined ponds. Our current BMP guideline for the production of 229-mm channel catfish which recommends flushing of ponds with fresh water only when water quality demands it, which is similar to the conservative strategy used in this study, was supported by the results of this study. Both treatments promoted good water quality with DO levels of 5.3-9.1 mg/L, pH of 8.0-8.7, un-ionized ammonia concentrations of 0.018-0.24 mg N/L, and temperatures of 27-30^{o}C. These water quality variables supported good catfish production with survival, growth rate, fish biomass, fish length, and feed conversion of 87.5-91.0%, 1.8-1.9 mm/d, 2,592-2,750 kg/ha, 253 mm, and 1.2-1.3, respectively. We propose that these results constitute baseline information on water quality and production performance for 229-mm channel catfish production in plastic-lined ponds. Future research should consider improving this baseline information for the conservative water use strategy.

INTRODUCTION

Pond water exchange (flushing) is frequently used in Texas Parks and Wildlife Department (TPWD) channel catfish *Ictalurus punctatus* grow-out ponds as a pond management tool. However, the timing, rate, and reasons for flushing ponds vary among fish hatcheries. Beside the immediate need to flush ponds to correct an issue such as critically low dissolved oxygen (DO) or high ammonia concentration that can kill fish, the decision to flush ponds also is often based on other factors. These factors include water availability, pumping cost, morning DO concentration, ammonia concentration, water temperature, pH, availability of aeration, disease outbreaks, and color of pond water (the perceived density of phytoplankton bloom). These factors may be categorized into objective (e.g., morning DO < 4.0) and subjective (e.g., pond color too green) criteria. Disparate use of these decision-making criteria, especially the subjective criteria, often results in inconsistent use of water exchanges among hatcheries which complicates the evaluation of fish production inputs and outputs. Furthermore, pond flushing often is used prophylactically at TPWD hatcheries based on the historical timing of disease outbreaks or poor water quality with water exchange increasing as the fish grow and pond biomass and feeding rates increase. Such flushing is used to reduce phytoplankton biomass and organic matter, but rarely is this tactic based on objective criteria. When pond flushing is used prophylactically and based on subjective criteria there is no guarantee the water use is not wasteful.

In addition, flushing can cause a reduction in biosecurity because all TPWD hatcheries rely on surface water supplies with established fish populations. These waters are potential disease vectors and flushing with these surface waters needs to be evaluated against the objective of maintaining optimal water quality for good catfish production. Characteristics of good catfish production include growth rate ≥ 1.7 mm/d, feed conversion [FCR] ≤ 1.2, and survival ≥ 70% (Wyatt et al. 2006) and those for optimal water quality are temperatures of 27 – 29°C, minimum DO of 5 mg/L, pH of 6.0-9.0, maximum un-ionized ammonia (UIA) concentration of 0.2 mg N/L (Tucker and Robinson 1990), and maximum nitrite concentration of 9 mg N/L (Wedemeyer 2001). What appears lacking is optimal water use or exchange rate required to achieve these optimal water quality characteristics and good catfish production.

Commercial catfish producers apparently use water exchange as a pond management tool more conservatively than TPWD fish culturists. They usually flush ponds twice a year to improve water quality (Tucker and Robinson 1990). In Alabama, most commercial catfish ponds are flushed completely only twice in a 15-year period (Boyd et al. 2007). These practices appear to be based on the recommendation that water exchange should not be used for managing DO in most freshwater ponds. Boyd (1990) probably made this recommendation partly because of the limited availability of water in catfish farming areas where water supplies are mainly from wells and the pumping costs are higher than the lower costs and higher oxygen transfer rate of aeration equipments. Nevertheless, research appears to support the notion that conservative water use may not be detrimental to catfish production. Seok et al. (1995) reared small catfish at densities of 2,457/ha in ponds that received only make-up water and were left un-drained for three years. Compared to drained ponds, un-drained ponds had more parasites but fish production was similar to that of the drained ponds. Cole and Boyd (1986) found that ponds stocked at densities similar to those typically used at TPWD hatcheries (17,300 fish/ha) and fed at a maximum rate of 112 kg/ha/d could be managed successfully with minimal aeration and only make-up water.

Unlike commercial catfish producers, TPWD pond managers use water liberally since ponds often have some water continuously flowed through them, especially later in the culture period when catfish biomass and feeding rates are high. This luxury is afforded by the ample gravity-flow water supplies to most TPWD hatcheries that range in capacity from 7,570 to 19,925 Lpm. A few studies provide support for liberal use of water. In intensive systems and small ponds, higher water exchange rates have increased fish production (Andrews et al. 1971; Allen 1974; Hopkins et al. 1993; Algazzar et al. 2008). Therefore, it may be argued that where water is available, liberal water use can be an effective pond management tool, particularly for intensive culture systems. However, aquaculture water use and effluent discharge have come under increased scrutiny and criticism in recent years because of the potential adverse economic and ecological impacts to source and receiving bodies of water (Boyd et al. 2008; Verdegem and Bosma 2009). In addition, water demand is increasing exponentially in most states, including Texas, because of increasing drought and human populations. It is estimated that Texas will need an additional 8.8 million acre-feet of water in 2060 (Texas Water Development Board 2006). Therefore, there is a need to develop standard water use strategies for aquaculture based on real need rather than perceived needs in order to use water efficiently and effectively. A perceived need for flushing is when the latter is assumed to remedy a situation which does not exist or for which the cause is unknown. A typical example of perceived need is when flushing becomes an unsupportable risk avoidance measure intended to insure fish survival.

In this study, we compared two methods of managing water quality in TPWD catfish production ponds: a conservative approach where ponds are flushed with fresh water when established water quality thresholds (morning DO < 4 mg/L or afternoon pH > 9.5) are met versus a liberal approach of continuous exchange of fresh water through ponds beginning at a predetermined time during 229-mm channel catfish production. The current TPWD best management practices (BMP) guidelines for channel catfish rearing ponds call for fresh water inflow into ponds only as needed to maintain acceptable water quality for catfish production (TPWD unpublished), which is essentially a conservative approach. This guideline was based on the fact that the added fresh water may present reduced biosecurity by introducing pathogens that can cause fish diseases as well as alter water chemistry or temperature that may be stressful to fish. We suspect either scenario can reduce catfish production; however, the effects of conservative and liberal water use on water quality and catfish production have not been tested at TPWD hatcheries with plastic-lined ponds. TPWD hatcheries have not rigorously documented water use in catfish production ponds despite routine collection of water quality and fish production data. This study, therefore, represents the first steps in TPWD efforts to broaden understanding of the management of catfish ponds by correlating water use information with that of water quality and catfish production. The objectives were: 1) develop baseline information on water quality characteristics and catfish production performance under the two water use strategies, 2) determine if the TPWD BMP guideline on water use in catfish ponds is warranted, and 3) determine the most efficient use of water for catfish production at TPWD fish hatcheries.

MATERIALS AND METHODS

Study Conditions

This study was conducted at three TPWD fish hatcheries: A. E. Wood hatchery (AEW) on the San Marcos River, Hays County; Possum Kingdom hatchery (PKFH) below Lake Possum Kingdom on the Brazos River, Palo Pinto County; and Dundee hatchery (DFH) below Lake Diversion on the Wichita River, Archer County. Thirty ponds, 10 ponds at each hatchery, were used for the study. All ponds were plastic-lined and those at AEW and DFH were each 0.40 and 0.41 ha with volumes of 4.7 M L and 3.9 M L, respectively. Ponds at PKFH averaged 0.28 ha (range 0.25 – 0.35) or 2.5 M L (range 2.4 – 4.1). Each pond was supplied with a single static tube aerator (20-cm diameter × 45-cm tall; RAMCO Sales, Inc., Cushing, OK) capable of supplying 0.45 – 0.90 kg oxygen/h. All ponds received continuous aeration beginning 30 d after fish stocking.

The waters for all three hatcheries are relatively hard with high mineral contents (Table 1). Salinity averages 2.9 and 1.4 ppt for DFH and PKFH, respectively but is negligible for AEW. The PKFH and DFH experience frequent toxic blooms of the harmful alga *Prymnesium parvum* in their sources of water supply and ponds, which requires treatment with ammonium sulfate (AS) to control blooms (Barkoh et al. 2010). The DFH treats ponds when filled and then prophylactically 2-3 times weekly to maintain control of blooms whereas PKFH treats ponds only when ponds are first filled and again if *P. parvum* cells are detected in water samples during the culture period. Ponds at DFH and PKFH were filled 11-12 d prior to fish stocking to allow initial AS treatments to eliminate *P. parvum* or reduce densities and the resulting ammonia levels to decrease to safe levels for sensitive fish (Barkoh at al. 2010). Ponds at AEW were filled 6-7 d prior to fish stocking.

Treatments

We evaluated liberal and conservative water use as treatments (Table 2). Ponds were randomly assigned to treatments which were implemented beginning 30 d after fish stocking (i.e., on the same day aeration of all ponds began) and continued to the day pond draining began to harvest the fish (day 70 after fish stocking). Liberal water use ponds received a sustained water exchange rate of approximately one pond volume per week. At AEW and DFH this was accomplished by opening a valve at the back of each pond to allow fresh water to flow through the pond over a weir at the front of the pond at a rate of approximately 379 L/min. Because PKFH did not have the infrastructure to install overflow weirs, the same exchange rate was achieved by lowering the pond water depth by approximately 1/3 three times per week and continuously refilling from a water supply valve at the back of the pond. Conservative water use ponds received no water except emergency pond flushing which was also available to liberal water use ponds. Emergency flushing was applied to ponds on an individual basis when an established criterion (morning DO < 4.0 mg/L or afternoon pH > 9.5) was met. A pond due for emergency flushing received fresh water at a rate of 757 L/min for 24-h accretive periods until the low DO or high pH condition was corrected. Water flow was measured daily, after each flow adjustment, by measuring the depth of water over a v-notched overflow weir (AEW), water height through a calibrated slotted vertical inlet pipe (DFH), or by approximating the replacement rate by lowering and refilling the pond by a standard height and known volume for each filing interval (PKFH).

Water Quality

Pond water temperature, DO, and pH were monitored twice daily at 0600 and 1500 hours with a 650 MDS handheld meter fitted with a YSI 600 XL multiprobe sensor (Yellow Springs Instruments, Yellow Springs, Ohio). The probe was calibrated daily before first use. Ammonia concentrations were measured twice weekly from each pond with an ion–selective electrode using the standard method 4500D (APHA 1998). Chlorophyll *a* (uncorrected for pheophyton) was determined spectrophotometrically (10200H; APHA 1998). Water samples for ammonia and chlorophyll *a* measurements were collected mid-morning at a depth of approximately 30 cm near but outside the pond kettle, the farthest location from the incoming water source, in opaque polyethylene bottles and processed immediately. For chlorophyll *a,* 50-100 mL of water from each pond was filtered through a Whatman glass fiber filter. These filters were individually wrapped in aluminum foil, frozen, and shipped overnight to the TPWD Inland Fisheries Analytical Services Laboratory (San Marcos, Texas) for analysis.

Catfish Production

Fish stocking and harvest.—Ponds were stocked with 90-mm total length channel catfish fingerlings which were produced at the AEW from a captive broodstock. A pond stocking density of 20,731 fish/ha was selected for all ponds to simultaneously equalize fish density and limit the maximum pond population size to 8,500 fish/pond. This maximum pond population size was selected because it appears to reduce the incidence of disease outbreaks in TPWD channel catfish grow-out ponds (TPWD unpublished). This selected stocking density limited the maximum population size at PKFH to 7,193 fish because PKFH ponds were smaller (Table 3). All but two of the 30 ponds were stocked on 13 and 14 July 2010. Two ponds at AEW (one for each treatment) were stocked on 19 July 2010 when additional fish became available. Fish mortalities were recorded daily for each pond. Fish length and average weight at stocking and harvest were estimated from a sample of at least 30 fish from each pond. All fish were weighed into and out of each pond to determine total biomass and to estimate numbers. Fish harvest was delayed for some ponds because of reservoir stocking scheduling issues or disease outbreaks.

Feeding.—Fish were fed 32% protein floating catfish pellets (Rangen Inc., Angleton, Texas), and pellet size was increased from 1.5 to 4.8 mm as the fish grew. Target feeding rates were estimated, based on historical estimates of fish growth rate and biomass (Wyatt et al. 2006), to be 3.6-6.5% of estimated fish biomass depending on water temperature and fish length. However, fish were generally not fed more than they would consume in a 15-min period (satiation) twice daily. The actual amount of feed for each pond was recorded daily. The AEW and DFH fed the fish twice daily 7 days-a-week whereas PKFH fed the fish twice daily from Monday to Friday but once daily (1/2 ration) on Saturdays and Sundays.

Data Analysis

Water quality, water use, and feeding (quantity of feed and FCR) data were analyzed using the General Linear Models Procedure of SYSTAT 12 to assess the effects of treatment, hatchery, and day as well as their interactions. When the effects of hatchery, day, and interactions were significant, we used Tukey's Honestly-Significant-Difference Test to determine differences among the means. In addition, we examined the water quality trends graphically because individual daily values (e.g., extremely low DO concentration) may affect fish production outcomes in spite of apparent similarity or dissimilarity of overall treatment mean values. To analyze these data, we used a two sample *t*-test on daily means to determine treatment effect. For some water quality variables, we used two-sample variance test to determine if the water quality variability differed between treatments. Because of differences in culture days that resulted from fish harvest delays, water quality variables were compared between treatments or among hatcheries up to day 70 of the fish culture period. This allowed all ponds to be included in the analyses. Fish stocking and harvest data as well as chlorophyll *a* data were analyzed by analysis of variance with SYSTAT 12 (SYSTAT 2007) to assess the effects of treatment, hatchery, and hatchery x treatment interaction. Where necessary, appropriate data transformation was performed before statistical analysis. Percent survival data were arcsine transformed to improve homogeneity of variance, and mortality data were log + 1 transformed due to zeroes in the data and to improve normality and homogeneity of variance. Chlorophyll *a* data were log transformed to improve homogeneity of variance and normality. For all statistical comparisons differences were considered significant at $P \leq 0.05$.

RESULTS AND DISCUSSION

Water Quantity and Quality

Emergency flushing was required to reduce pH below 9.5 in all ponds in both treatments at AEW and DFH and one conservative treatment pond at PKFH prior to day 30 when aeration was started in all ponds and treatments were implemented (Figure 1). After implementation of treatments (≥ day 30), emergency flushing was required in all conservative ponds and some liberal ponds to manage against low DO (Figure 1) especially as catfish biomass and feeding rates increased. Conservative treatment ponds required flushing 15, 35, and 19 times at AEW, PKFH, and DFH, respectively, which resulted in 2-4, 2-13, and 1-7 flushes per pond at AEW, PKFH, and DFH in that order over the course of the study. Despite constant water flows through liberal treatment ponds**,** emergency flushing was required in individual ponds 6 times at PKFH and 2 times at AEW. Liberal treatment ponds at DFH did not require emergency flushing.

Mean total water use was significantly different among hatcheries and between treatments ($P= 0.0000$; Table 4). Overall, the quantity of water used averaged 19.3 M L/pond for liberal ponds and 3.3 M L/pond for conservative ponds during the study period (days 30-70); thus the liberal treatment required approximately a 6-fold overall increase in water use compared to the conservative treatment. Similarly, water use averaged a 5.8-, 4.7-, and 10.8-fold increase in liberal ponds compared to conservative ponds at AEW, DFH, and PKFH, respectively. Average pond water use and average water flow at PKFH were significantly less in both conservative ($P \leq 0.022$) and liberal ($P = 0.000$) treatments than the values for AEW and DFH primarily because ponds there were smaller and the drain-and-fill technique limited the rate at which pond water could be exchanged. Whereas at AEW and DFH fresh water was applied continuously by flow-through for the liberal treatment or when required in conservative ponds, at PKFH exchanging water first required time to remove a substantial portion of the existing water volume before the pond could be refilled. Boyd (1990) indicated that the drain-and-fill technique of water exchange is superior because it assures amelioration of bad water quality characteristics proportionally to the volume of pond water exchanged (e.g., 50% reduction in ammonia with 50% replacement of pond water). However, we found that because of the time required to drain and refill a pond, the drain-and-fill method has the potential to continue to expose fish to poor water quality during the draw-down and refilling interval. Also it requires more manpower to observe pond water levels whereas flushing ponds that have overflow weirs simply requires opening a valve to the desired flow-rate and no additional manpower.

For all hatcheries, the observed average water exchange for the liberal treatment of 4.9 pond volumes was less than the target exchange of 5.7 volumes based on the exchange rate of one pond volume per week. The DFH water exchanges for the liberal and conservative treatments were significantly higher than those for PKFH (P=0.040 and P=0.006, respectively; Table 4). The AEW water exchanges for both treatments were similar to those of PKFH and DFH. These results may be explained by observed differences in water flow monitoring and data collection protocols among hatcheries that may have reduced the variability in the water exchange data and inflated the statistical differences in water use between DFH and the other hatcheries. At AEW, water flow rates were monitored by measuring the height of water through overflow weirs. These heights were recorded daily prior to water flow adjustments to the target height. This method resulted in some variability in flow rates as hatchery water use and supply reservoir depth effected supply pipe pressures by the following morning when measurements were taken again. At PKFH ponds were drained to a target depth and refilled and the variability in water supply was reflected in the variable times for refilling. However, at DFH water flows into liberal treatment ponds were adjusted each morning to a predetermined height of the calibrated inlet supply pipe. Once adjustments were made, if necessary, and the target flow rate was achieved, that target was recorded as the daily flow value. As a result, there was little variability in water flow rates for the liberal treatment at DFH (Figure 1; Table 4). In spite of these differences in water flow measurement techniques among hatcheries, we feel confident that biologically significant different exchange rates were achieved between the treatments at each hatchery. However, whether or not the exchange rates achieved for each treatment at DFH were truly different from those of PKFH is unclear.

Dissolved oxygen concentration was variable over time (Figure 3) and between treatments or hatcheries (Table 5). Morning DO decreased over time as fish biomass and feeding rates increased while daylight hours deceased over the course of the study. Increasing fish biomass and feeding rates are associated with increasing DO uptake by fish and microbial degradation of organic matter in ponds. In contrast, decreasing daylight hours results in decreasing DO production through photosynthesis. The net effect of these processes was the observed DO declines over the course of the study. Morning DO trends were higher in liberal than in conservative treatment ponds (Figure 3). Morning DO differed significantly between treatments, averaging 6.1 mg/L in liberal treatment ponds and 5.3 mg/L in conservative treatment ponds (Table 5) - a difference of about 0.8 mg/L. Morning DO was highest at AEW and lowest at PKFH. Since similar water exchange rates were achieved in ponds in both treatments at AEW and PKFH, this finding does not seem to support Boyd's (1990) observation that the drain-and-fill approach is superior to flow-through for managing pond water quality with fresh water. The difference in morning DO between treatments at AEW was also of higher magnitude (Figure 3) which seems to support the notion that the best method of managing pond water quality should achieve the greatest difference in water quality improvement between high and low water exchange rates. However, the change in water quality (e.g., DO) between high and low water exchanges depends on the quality of the incoming water relative to that of the receiving water (Boyd 1990). Incoming water DO averaged 8.3 mg/L at AEW and 5.6 mg/L at PKFH. While both water supplies were of superior or equal quality with respect to DO compared to the pond water being removed, it is possible that the incoming water quality unequally affected the difference and magnitude of the difference in DO between treatments. Conversely, the DO of the incoming water at DFH averaged 3.7 mg/L and was generally lower than the DO of either treatment. Therefore, the higher DO in liberal treatment ponds may be due to better removal of excess phytoplankton and organic matter which would support the practice of using continuous water flow-through as a prophylactic measure of managing pond water quality. It appears that where incoming water quality is equal to or worse than that of the receiving pond water, the liberal strategy may be better than the conservative strategy.

Incidences of low morning DO ($\leq$ 4.0 mg/L) were more frequent in conservative ponds. There were 8 such incidences in liberal ponds compared to 69 in conservative ponds (Figure 4). However, these incidences of low morning DO in conservative ponds never persisted through the afternoons. These low morning DO levels either self-corrected as the day progressed on sunny days or were corrected by management action (flushing). Similarly, the absolute minimum morning DO measured in conservative ponds was 1.3 mg/L versus 3.4 mg/L in liberal ponds. Liberal water use was better at maintaining higher morning DO levels than conservative water use. In contrast to morning DO, afternoon DO trends were much more similar between treatments within a hatchery and across hatcheries (data not shown).

While the liberal water use treatment provided a higher margin of safety for pond DO, the conservative treatment was as effective in managing pond DO. This is evidenced by the lack of persistent low DO in conservative ponds through the afternoons. Also, since disease outbreaks and associated fish mortalities were not significantly higher in conservative ponds, it appears channel catfish can tolerate these temporary episodes of low morning DO with no adverse effect on fish production, at least, at the densities used in this study.

Ponds water temperatures increased among hatcheries from north to south (i.e. AEW > PKFH >DFH; Table 5). Morning or afternoon pond water temperatures were similar between treatments ($P \geq 0.084$) and varied no more than 3°C among hatcheries (Table 5). In general, morning pond water temperatures gradually decreased from a peak of about 32°C during the first week to 22°C by time of fish harvest (Figure 5). Afternoon temperatures were typically 2°C higher than morning temperatures. We did not see the temperature trends of previous years where pond water temperatures were drastically reduced when ponds were flushed to correct low DO concentrations or to minimize the effects of diseases on the fish. Typically, these incidences coincided with cloud cover and early fall cool fronts late in the year. During this study, the weather was moderate and disease outbreak was minimal. Our results suggest that both treatments were more effective against low DO and disease outbreaks than the typical TPWD pond management strategy has been probably because this study required constant attention to DO and pH management.

Pond water pH was significantly different among hatcheries and between treatments (Table 5) largely because of differential pond management strategies (AS applications and feeding) among hatcheries as well as treatment effect. Ammonium sulfate was used regularly by DFH and once by PKFH to control *P. parvum* whereas AEW did not use any. Since AS is a fertilizer (source of N), it promoted increased phytoplankton biomass (chlorophyll *a*) and photosynthesis which in turn supported higher pH levels (Boyd 1990; Wedemeyer 2001) at DFH compared to the other two hatcheries. In addition, excess feed, *albeit* minimal in this study because fish were fed to satiation, and fish excreta also contributed to the nutrient inputs of ponds (Boyd 1990) to support increased phytoplankton biomass and photosynthesis. Conversely, flushing disproportionally removed phytoplankton and nutrients from ponds (Boyd 1990) resulting in unequal net gain of phytoplankton biomass. Liberal ponds lost more nutrients and phytoplankton biomass due to the larger amounts of water flowed through them, and thus had lower pH on most days than conservative ponds which experienced lower losses of nutrients and phytoplankton (Figure 6, Table 5). Daily pH differed by as much as 1 pH unit between treatments on some days. Within hatcheries, afternoon pH trended lower in liberal ponds than in conservative ponds. Daily differences in pH were occasionally significant at PKFH (8 of 40 d) but differences at DFH and AEW were significantly more frequent and much greater. Pond pH was significantly higher in conservative ponds at AEW on 23 of 40 d and at DFH on 22 of 40 d (Figure 6).

The pH trends generally were similar among hatcheries, decreasing over the course of the study which may be explained mainly by decreasing daylight hours and phytoplankton biomass during autumn months and increasing fish biomass and feeding rates as the study progressed. These conditions probably promoted increasing net gain in CO_2 between production through respiration by fish and phytoplankton as well as organic matter degradation by bacteria at all times and uptake by phytoplankton for photosynthesis only during daylight hours. As the net gain in CO_2 increased overtime, pond water pH declined. At all hatcheries the differences in daily pH between liberal and conservative treatments may be due to lesser CO_2 uptake in liberal ponds because of lower phytoplankton biomass resulting from removal by flushing. Because significant differences in daily pH were less at PKFH compared to AEW or DFH, we hypothesize that the drain-and-fill strategy does not remove excess phytoplankton and organic matter as well as flushing does. The chlorophyll *a* results (Figure 8) seem the support this hypothesis; however, future studies should test it.

Whereas pond water management aims at improving water quality, we did not see an improvement in pH in liberal (drain-and-fill) ponds at PKFH even though more water was used in these ponds than in the conservative ponds compared to treatments at the other hatcheries. The differences in water use between liberal and conservative treatments were 10.8-, 5.8-, and 4.7-fold higher at PKFH, AEW, and DFH, respectively. Yet afternoon pH was similar between treatments at PKFH (Figure 6; $P = 0.842$) but significantly different between treatments at AEW (P=0.000) and DFH (P=0.029). These results contradict Boyd (1990) who stated that the drain-and-fill method of water exchange is a superior approach to pond water quality management. Incoming water pH at both AEW and PKFH averaged 7.8 and this water improved pH in flow-through ponds at AEW but not in drain-and-fill ponds at PKFH. Because the drain-and-fill method used at PKFH did not result in a significant difference in pH between treatments, we suspect that the drain-and-fill method did not remove adequate waste, nutrients and phytoplankton from ponds relative to the conservative method unlike the other hatcheries. Instead, as ponds were lowered fish were more concentrated and nutrients from waste and feeding became more concentrated in a lower volume of water prior to the addition of freshwater. Thus, when the ponds were refilled proportional reductions in undesirable water quality were not achieved because an increase in the undesirable water quality had occurred during the draining period.

Ammonia concentration significantly differed among hatcheries ($P = 0.000$) but not between treatments within hatchery or across hatcheries ($P = 0.249$; Table 5). Mean ammonia concentration was significantly higher at DFH than at AEW or PKFH. Conversely, ammonia concentration was statistically similar between AEW and PKFH. The differences in ammonia concentration among hatcheries are attributable mainly to differences in the use of AS to control *P. parvum* blooms. At AEW, where no AS was used, ammonia concentrations were near the detection limit of the analytical method (0.02 mg NH_4-N/L; Figure 7) and averaged 0.04 mg NH_4-N/L. The PKFH made an initial application of AS prior to fish stocking, without additional applications, and ammonia concentrations declined to near the detection limit by day 20 (Figure 7) and averaged 0.02 mg NH_4-N/L (Table 5). Because ammonia concentrations at AEW and PKFH were near the detection limit, any analysis of variance between treatments could be invalid and thus our only conclusion for these two hatcheries is that ammonia concentrations in both treatments were so low to be of no consequence to fish culture. Therefore, the use of fresh water to manage for ammonia in ponds stocked at typical TPWD densities and fed at typical TPWD feeding rates is unwarranted. In contrast, DFH made weekly application of AS to maintain adequate un-ionized ammonia concentrations (> 0.14 mg NH_3-N/L; Barkoh et al. 2010) to prevent *P. parvum* blooms. Consequently, ammonia concentration at DFH (0.31 mg NH_4-N/L) was highest among the hatcheries. Fish feed and excreta are sources of ammonia in fish culture ponds (Piper et al. 1982; Boyd 1990), and Boyd (1990) estimated that a 32% protein feed would produce about 30.7 g of NH_4-N/kg of feed and be excreted. Based on this estimate, we calculated that by day 70 a total of 8.5, 7.6, and 4.5 mg NH_4-N/L at AEW, DFH, and PKFH respectively would have accumulated in ponds by feeding the fish. Given that ammonia was barely detectable at AEW and PKFH by day 70 where little or no AS was used, we conclude that these ponds had the capacity to effectively metabolize the excreted ammonia. This further supports our conclusion that using pond flushing prophylactically to manage ammonia is unwarranted at the fish densities and time span used in this study.

Within hatchery, ammonia did not significantly differ between treatments. Because constant water flow through liberal ponds reduced ammonia concentrations between days 40-60 at DFH (Figure 7), additional AS applications were required to maintain adequate UIA residuals to control *P. parvum*. As a result, a total of 80 kg more of AS was applied to the five liberal treatment ponds at DFH than the conservative treatment ponds. Despite the differential need for AS, UIA concentrations were statistically similar between treatments ($P = 0.782$) and averaged 0.074 mg NH_3-N/L. Similarity of UIA concentrations was achieved in spite of different water exchange rates by managing ponds individually and applying AS based on pH and temperature of the individual pond to achieve the target UIA rate for *P. parvum* control.

The un-ionized fraction of total ammonia, which is responsible for ammonia's harmful effects (Colt and Tchobanoglous 1976; Meade 1985; Sheehan and Lewis 1986; Bader and Grizzle 1992), correlates with temperature and pH (Emerson et al. 1975; Paley et al. 1993). The afternoon UIA-N values, which were higher than the morning values, were 0.018 and 0.024 mg/L for liberal and conservative treatments, and 0.008, 0.081 and 0.002 mg/L for AEW, DFH and PKFH, respectively. These UIA-N concentrations are far lower than the 24-h LC_{50} concentration of 2.24 mg NH_3-N/L at pH 8.8 reported by Sheehan and Lewis (1986) and the 24-h LC_{50} concentration of 1.49 mg NH_3-N/L at pH 9 reported by Tomasso et al. (1980). These UIA-N concentrations are also lower than the lowest-observable-effect concentration of 0.175 mg NH_3-N/L for 7-d-old catfish (Bader and Grizzle 1992) as well as the 0.12 mg NH_3-N/L above which growth of channel catfish fingerlings is reduced by chronic exposure (Robinette 1976). Thus, we conclude that the ammonia concentrations observed in this study were suitable for 90-229-mm channel catfish production. This conclusion is supported by the lack of significant difference in either fish growth or survival between treatments within hatchery or across hatcheries (Tables 6 and 7). Fish survival and growth are the two main variables affected by lethal and sublethal levels of ammonia, respectively (Russo and Thurston 1991; Anderson 1993a).

Chlorophyll *a*, a surrogate measure of phytoplankton biomass, did not significantly differ between treatments ($P = 0.97$) but did differ among hatcheries ($P = 0.043$; Table 5). The difference in chlorophyll *a* concentration among hatcheries was probably due, in part, to the differential use of AS to control *P. parvum.* Chlorophyll *a* increased over time in both treatments at all hatcheries (Figure 8). After day 30 or 40, depending on the hatchery, daily chlorophyll *a* was consistently higher in conservative treatment ponds than in liberal treatment ponds. This was a consequence of the differential net phytoplankton biomass in ponds due to the different water exchange rates between treatments. However, the differences were significant only at DFH although variability in the data was higher and pond volume exchange ratio (Liberal:Conservative = 4.7:1) was similar to that of AEW (5.8:1) and lower compared to PKFH (10.8:1). At DFH, daily chlorophyll *a* concentrations in some conservative ponds exceeded 300 μg/L on some sampling days. More frequent application of AS to control *P. parvum* at DFH coupled with conservative management of ponds as individuals may explain, at least partly, the high and varied chlorophyll *a* values in these ponds. The lack of significant difference in chlorophyll *a* between treatments, in terms of overall mean or daily mean values, was probably due to the high variability in the data. The mean and associated variance values of chlorophyll *a* were 81 and 6,313, respectively for the conservative treatment compared to 37 and 580, respectively for the liberal treatment.

Catfish Production

Fish stocking.—Mean values of pond size, number and weight of fish, and biomass of fish stocked differed among hatcheries ($P < 0.05$; Table 6). Ponds were smallest at PKFH and consequently received the least mean number and weight of fish. Conversely, mean pond sizes or numbers of fish stocked were greater for AEW and DFH than PKFH and similar. Although, mean number of fish was similar between AEW and DFH, two ponds in each treatment at DFH received more fish than the target maximum of 8,500 fish per pond (Table 3). Stocking of these additional fish was considered necessary to ensure that the 229-mm catfish production goal was achieved. The stocking density for all ponds averaged 21,750 fish/ha which was 5%

higher than the target stocking density of 20,731 fish/ha. Mean fish weight and biomass were greater for AEW compared to DFH. Overall, pond stocking statistics did not significantly differ between conservative and liberal treatments ($P > 0.05$; Table 6) primarily because values of stocking variables were weighted by pond size. Similarly, pond stocking statistics did not differ due to combined hatchery and treatment effect. These results are artifacts of the study design that equalized stocking variables among ponds and hatcheries, and between treatments.

Fish production.—Culture days averaged 91 d (70 – 113 d) among ponds (Table 3) and significantly differed among hatcheries ($P = 0.001$) and between treatments ($P = 0.048$; Table 6). Mean culture days were 82, 90, and 100 d for AEW, PKFH, and DFH, respectively; and 87 and 94 d for conservative and liberal treatments, respectively. These differences resulted from unexpected delays in harvesting some of the ponds toward the end of the study. The quantity of fish produced exceeded that requested by management and a distribution plan for the excess fish took time to develop, creating fish harvest delays. Furthermore three DFH ponds, two liberal ponds and one conservative pond, experienced concurrent outbreaks of *Trichodina* spp. and *Aeromonas hydrophila* after the anticipated time of fish harvest (day 90 post-stocking) and further delayed harvest of these ponds. Consequently, culture days became dissimilar among hatcheries. However, within each hatchery, culture days did not significantly differ between treatments (Table 7) because all hatcheries tried to minimize any potential differences in culture days between treatments by staggering pond harvests.

Fish production was excellent for both liberal and conservative treatments across hatcheries and statistically similar between treatments (Table 6). Despite the dissimilar culture days, weight of feed fed to fish per pond was the only harvest variable significantly different between treatments (Table 6; $P = 0.019$). The average difference in feed weight was 141 kg/pond or equivalent to 3 – 4 d of feeding and resulted from withholding feeding of fish in ponds that experienced DO < 5.0 mg/L, which began around day 50 of the culture period. The reduction of feeding did not significantly affect FCR or any of the measured fish harvest variables ($P > 0.05$; Table 6), an indication that the fish were not underfed. Fish growth rate was marginally reduced in conservative ponds ($P = 0.058$) probably by the restricted feeding. These ponds were the majority of the ponds that experienced low DO levels and consequently more restricted feeding. However, the growth rate difference of 0.1 mm/d would have resulted in only a difference of 9 mm in total growth during a typical 90-d culture period which from a practical standpoint is insignificant in the context of overall fish production.

Unlike the effects of treatment on harvest variables, hatchery effect was significant on the weight of feed used, fish length, biomass, size, growth rate, and mortality ($P < 0.05$; Table 6). The number and weight of fish harvested were also significantly different among hatcheries, but this was due to the different pond sizes among hatcheries as previously mentioned. Fish were largest at AEW largely due to differences in feeding strategy among hatcheries. All hatcheries used the same method to estimate feed amounts; however, AEW fed the fish more followed by DFH and PKFH, in that order (Figure 9). The AEW and DFH fed fish twice daily 7 days-a-week whereas PKFH fed fish twice daily on weekdays and once daily on weekends. In addition, DFH reduced feeding rates once fish were near the 229-mm target length (about day 65) in anticipation of harvest whereas PKFH and AEW maintained or continued to increase feeding rates. The high fish mortality rate for DFH was due largely to

Trichodina spp. and *Aeromonas hydrophila* outbreaks in two liberal ponds and one conservative pond that killed fish daily over a one-week period, peaking at 100-400 fish/d. Nonetheless, catfish survival for DFH was not significantly different from the survival rates at the other two hatcheries.

Input Costs

Among hatcheries, the cost of water use was consistently higher for the liberal than for the conservative treatment (Table 8). For AEW and DFH the cost of water for the liberal treatment was more than 3-fold that of the conservative treatment whereas at PKFH the cost was approximately 12-fold. In addition, AEW incurred water pumping costs of $419/pond and $113/pond for liberal and conservative treatments, respectively. The DFH and PKFH get water by gravity flow and thus incurred no water pumping costs. Currently, River Authorities provide water to TPWD fish hatcheries at no cost. The only water supply cost to the agency is pumping cost at AEW. Nonetheless, we estimated cost of water based on current market value to compare this input cost between treatments. This is important because with the expected increased demand for water in many states, including Texas (Texas Water Development Board 2006)), the cost of water can become substantial for most catfish producers in the near future. Another input variable affected by pond water exchanges was the AS used to control *P. parvum*. A total of 317 kg AS/pond was applied to liberal treatment ponds compared to 221 kg AS/pond for conservative treatment ponds at DFH. The cost was $135.36/pond for liberal ponds and $94.37/pond for conservative ponds. For the 10 ponds used at DFH, $409.90 could be saved by using only the conservative treatment. These results show that liberal water use can significantly increase catfish production input cost. Because pond management input correlates inversely with catfish production efficiency or profit (Boyd and Tucker 1998), water quality management in catfish ponds should minimize input cost. Our results indicate that conservative water use was better than liberal water use in optimizing catfish production by minimizing input cost.

Another input cost that was not quantified in this study is labor or man-hours. Because the conservative treatment received 77 flushes compared to 16 flushes for the liberal treatment, a fair argument against the conservative treatment might be excessive manpower requirement to physically turn water on and off into ponds. However, because DO of ponds are monitored daily as standard practice at TPWD hatcheries, water flows into ponds can be done along with DO monitoring and thereby eliminate the need for additional trips to the ponds. Combining these two activities, as needed, would result in less time or workload than making separate trips to ponds. Liberal ponds would also be monitored daily for DO and flushed as needed. Therefore, we suspect the difference in man-hours between liberal and conservative water use would be insignificant if flushing of pond is combined with a routine activity.

SUMMARY

In this study, both liberal and conservative water use had a similar effect on channel catfish production by promoting similarly good water quality for the fish. Both treatments promoted DO levels of 5.3-9.1 mg/L, pH of 8.0-8.7, un-ionized ammonia concentrations of 0.018-0.024 mg N/L, and temperatures of 27-30^{o}C. These water quality characteristics are similar or better than those considered optimal for catfish culture (Tucker and Robinson 1990). Fish survival and growth rates were 87.5-91.0% and 1.8-1.9 mm/d, respectively and better than those considered good catfish production results. The FCR values were 1.2-1.3 and similar to the 1.2 for good catfish production (Wyatt et al. 2006). These water quality and catfish production results should constitute baseline information for further examination to improve catfish production efficiency. We recommend that future studies examine the pH < 9.5 criterion used in pond water management. If 90-229-mm channel catfish can tolerate higher pH levels then further reductions in water use could be achieved with the conservative water use strategy to further improve catfish production efficiency. We also suggest studies aim at defining optimal water use for 229-mm channel catfish production in plastic-lined ponds.

Catfish production was similar between liberal and conservative treatments. However, input cost was lower for the conservative treatment resulting in better catfish production efficiency than the liberal treatment. Thus, we conclude that the conservative strategy would provide better use of water at TPWD fish hatcheries. However, because all potential input costs (e.g., man-hours) were not assessed in this study, we recommend that future studies examine routine input costs that can significantly influence production efficiency using study designs that minimize input costs, such as man-hours, though multi-tasking. We believe that combining pond flushing and water quality monitoring activities would result in a lower cost than the sum of the separate activities.

The current TPWD BMP recommendation is to use flow-through water in channel catfish fingerling grow-out ponds only when water quality demands it. We made this recommendation based on the theory that liberal water use would lead to increased risk of diseases where water supplies are not bio-secure. In previous years, we had observed substantial disease outbreaks near the end of the culture period when ponds were flushed heavily and such flushing drastically reduced pond water temperatures. We attributed the disease outbreaks to stress on the fish due to rapid temperature changes and likely introduction of parasites or pathogens. Our theory was not proven in this study because of the lack of significant disease outbreaks for the liberal treatment. Disease outbreak was even more minimal for the conservative water use treatment; therefore, there is no evidence from this study that ponds need a constant flow of fresh water to maintain good fish health. The present results suggest that conservative water use is better than liberal water use because it saves money on water use and other inputs without compromising fish production – supporting the merit of our BMP guidelines.

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TABLE 1.—Arithmetic mean (maximum – minimum) values of water quality characteristics of the water supplies for the A. E. Wood (AEW), Dundee (DFH), and Possum Kingdom (PKFH) fish hatcheries. Data from three years (2008-2010) of quarterly water sampling (Texas Parks and Wildlife, Inland Fisheries Division, Analytical Services Laboratory, San Marcos, Texas).

Variables	AEW	DFH	PKFH
Conductivity (µmhos/cm @ 25°C)	564 (174)	4,526 (1,470)	2,654 (1,633)
Total dissolved solids (mg/L)	378 (117)	2,837 (940)	1,558 (761)
Total suspended solids (mg/L)	3.1 (2.4)	21.8 (41.8)	4.0 (2.4)
Hardness (mg/L)	294 (108)	813 (370)	418 (189)
NH_4-N (mg/L)	0.009 (0.003)	0.033 (0.030)	0.034 (0.024)
Fluoride (mg/L)	0.174 (0.101)	0.174 (0.248)	0.149 (0.258)
Chloride (mg/L)	23 (42)	1,128 (1761)	566 (450)
Sulfate (mg/L)	25 (16)	675 (1102)	250 (256)
Calcium (mg/L)	93 (36)	216 (103)	418 (189)
Magnesium (mg/L)	15 (7)	66 (29)	31 (19)
Sodium (mg/L)	14 (6)	602 (29)	358 (322)
Potassium (mg/L)	2.1 (0.8)	17.7 (8.5)	13.6 (6.0)
Iron (mg/L)	0.144 (0.730)	0.511(1.807)	0.019 (0.050)
Silicon (mg/L)	5.1 (3.7)	3.7 (4.8)	4.0 (1.8)

TABLE 2.— Conservative and liberal water use treatment protocols for producing 229-mm channel catfish at three Texas Parks and Wildlife Department fish hatcheries in 2010.

Treatment	Continuous water use*	Emergency pond flushing**	Continuous aeration*
Conservative	None	If morning DO < 4.0 mg/L or afternoon pH > 9.5 flush at an exchange rate of 3.5 d (757 L/min) until morning DO or afternoon pH is corrected	Beginning August 15th or the first incidence of average treatment morning DO < 5.0 mg/L
Liberal	One water exchange per week (379 L/min) beginning August 15th or the first date average morning DO < 5.0 mg/L		

* Applied treatment wide ** Applied to individual ponds

TABLE 3.—Stocking and harvest statistics for 30 channel catfish ponds managed under conservative or liberal water exchange regimen at the A. E. Wood (AEW), Dundee (DFH), and Possum Kingdom (PFKH) fish hatcheries in 2010.

			Stocking					Harvest								
Hatchery	Treatment	Pond	Ha	Fish	Density (fish/ha)	Length (mm)	Biomass (kg)	Fish	Biomass (kg)	Length (mm)	Days	Growth (mm/d)	Feed (kg)	FCR	Density (fish/ha)	Survival (%)
AEW	Conservative	39	0.40	8,712	21,780	93	53.4	8,360	1,186	262	79	2.1	1,361	1.2	20,900	96
		43	0.40	8,588	21,470	87	48.7	6,971	1,219	262	84	2.1	1,543	1.3	17,428	81
		47	0.40	8,524	21,310	92	44.7	7,108	1,123	259	79	2.1	1,347	1.2	17,770	83
		48	0.40	8,730	21,825	88	47.0	7,711	1,581	274	89	2.1	1,872	1.2	19,278	88
		50	0.40	8,609	21,523	92	52.1	7,163	1,322	265	82	2.1	1,430	1.1	17,908	83
	Liberal	36	0.40	8,669	21,673	92	45.4	8,763	1,265	254	70	2.3	1,471	1.2	21,908	101
		37	0.40	8,627	21,568	93	52.9	7,639	1,344	256	77	2.1	1,548	1.2	19,098	89
		41	0.40	8,558	21,395	87	48.5	7,182	1,546	266	90	2.0	2,150	1.4	17,955	84
		44	0.40	8,700	21,750	88	46.8	7,694	1,749	274	90	2.1	1,836	1.1	19,235	88
		49	0.40	8,636	21,590	92	52.2	7,508	1,526	264	82	2.1	1,855	1.3	18,770	87
DFH	Conservative	17	0.41	8,192	19,980	93	50.2	8,570	974	245	79	1.9	982	1.1	20,902	105
		21	0.41	8,354	20,376	93	51.2	7,738	1,031	254	91	1.8	1,085	1.1	18,873	93
		25	0.41	8,101	19,759	87	45.6	7,717	919	254	92	1.9	1,026	1.2	18,822	95
		29	0.41	9,874	24,083	88	44.2	9,101	1,183	262	99	1.8	1,237	1.1	22,198	92
		31	0.41	9,771	23,832	88	43.7	7,516	1,016	263	103	1.7	1,056	1.1	18,332	77
	Liberal	22	0.41	8,026	19,576	93	49.2	7,634	979	260	111	1.5	119	1.2	18,620	95
		24	0.41	8,221	20,051	87	46.6	8,017	941	254	86	2.0	1,073	1.2	19,554	98
		28	0.41	8,059	19,656	87	45.7	5,291	545	257	113	1.5	1,107	2.2	12,905	66
		30	0.41	10,484	25,571	88	46.9	6,564	858	263	111	1.6	1,265	1.6	16,010	63
		32	0.41	9,603	23,422	88	43.0	7,307	1,012	263	110	1.6	1,108	1.1	17,822	76
PKFH	Conservative	30	0.25	5,024	20,096	89	25.2	4,584	491	238	99	1.5	587	1.3	18,336	91
		35	0.27	6,068	22,474	89	32.1	6,062	574	240	84	1.8	613	1.1	22,452	100
		36	0.28	6,493	23,189	89	35.3	6,177	594	234	84	1.7	597	1.1	22,061	95
		39	0.30	5,951	19,837	94	33.0	5,031	606	245	83	1.8	621	1.1	16,770	85
		40	0.33	7,193	21,797	91	38.3	7,228	688	234	84	1.7	695	1.1	21,903	100
	Liberal	31	0.25	5,040	20,160	90	24.9	4,801	660	242	100	1.5	736	1.2	19,204	95
		32	0.25	5,411	21,644	86	27.6	4,625	670	238	100	1.5	743	1.2	18,500	85
		34	0.26	5,936	22,831	86	30.4	5,667	683	235	99	1.5	712	1.1	21,796	95
		38	0.30	7,122	23,740	90	37.2	6,400	646	229	84	1.7	627	1.0	21,333	90
		42	0.35	6,698	19,137	91	40.7	6,703	700	242	84	1.8	738	1.1	19,151	100

TABLE 4.— Mean (SE) values of water use characteristics for channel catfish rearing ponds subjected to conservative or liberal water exchange regimen at three Texas Parks and Wildlife fish hatcheries in 2010. In each column values, excluding those for all hatcheries, bearing the same letter are not significantly different ($P > 0.05$). For all hatcheries values for the liberal treatment are significantly higher than those of the conservative treatment ($P \leq 0.05$).

Hatchery	Treatment	N	Average flow (LPM)	Total water used (million L)	Pond volumes exchanged
A.E. Wood		10	218 (51.7) ^{x}	12.9 (3.05) ^{x}	2.7 (0.65) ^{x}
	Conservative	5	65 (14.9) ^{y}	3.8 (0.88) ^{y}	0.8 (0.19) ^{yz}
	Liberal	5	371 (12.01) ^{a}	21.9 (0.71) ^{a}	4.6 (0.15) ^{ab}
Dundee		10	229 (48.7) ^{x}	13.5 (2.88) ^{x}	3.4 (0.73) ^{x}
	Conservative	5	83 (8.26) ^{y}	4.9 (0.48) ^{y}	1.2 (0.12) ^{y}
	Liberal	5	374 (0) ^{a}	22.1 (0) ^{a}	5.6 (0) ^{a}
Possum Kingdom		10	127 (37.8) ^{x}	7.5 (2.23) ^{x}	2.4 (0.70) ^{x}
	Conservative	5	20 (4.20) ^{z}	1.2 (0.25) ^{z}	0.4 (0.12) ^{z}
	Liberal	5	235 (25.74) ^{b}	13.9 (1.52) ^{b}	4.3 (0.53) ^{b}
All hatcheries		30	191 (2.2)	11.3 (1.60)	2.8 (0.39)
	Conservative	15	56 (8.89)	3.3 (0.52)	0.8 (0.12)
	Liberal	15	327 (19.43)	19.3 (1.15)	4.9 (0.22)

TABLE 5.— Mean (SE) values of water quality variables and water flow rates and associated *P*-values for 30 channel catfish production ponds managed under conservative or liberal water exchange regimen at the A. E. Wood (AEW), Dundee (DFH), and Possum Kingdom (PFKH) fish hatcheries in 2010. All data are for the period beyond 30 d after fish stocking when treatments were implemented.

	Morning DO (mg/L)	Afternoon DO (mg/L)	Morning pH	Afternoon pH	Morning temperature (°C)	Afternoon temperature (°C)	NH_4-N (mg/L)	Chlorophyll *a* (µg/L)	Flow (Lpm)
Hatchery									
AEW	6.4 (0.07)	10.8 (0.10)	8.0 (0.02)	8.5 (0.02)	29.0 (0.09)	30.5 (0.09)	0.04 (0.001)	43 (3)	218 (11)
DFH	5.5 (0.04)	7.9 (0.07)	8.2 (0.01)	8.8 (0.01)	26.5 (0.10)	28.3 (0.11)	0.31 (0.024)	116 (11)	229 (11)
PKFH	5.1 (0.04)	8.4 (0.06)	7.8 (0.02)	8.3 (0.02)	27.7 (0.11)	29.5 (0.14)	0.02 (0.0002)	27 (2)	128 (10)
Treatment									
Liberal	6.1 (0.04)	9.0 (0.08)	8.0 (0.01)	8.4 (0.01)	27.6 (0.09)	29.3 (0.09)	0.13 (0.014)	37 (2)	327 (6)
Conservative	5.3 (0.05)	9.1 (0.08)	8.1 (0.02)	8.7 (0.02)	27.9 (0.09)	29.5 (0.10)	0.10 (0.013)	81 (8)	56 (7)
Effect									
Hatchery	0.000	0.003	0.000	0.002	0.000	0.000	0.000	0.043	0.515
Day	0.431	0.000	0.000	0.000	0.000	0.000	0.752	0.000	0.000
Treatment (trt)	0.001	0.008	0.000	0.000	0.108	0.084	0.249	0.970	0.000
Hatchery x trt	0.354	0.251	0.000	0.000	0.432	0.733	0.375	0.329	0.002
Treatment x day	0.536	0.006	0.000	0.002	0.330	0.215	0.460	0.019	0.000
Hatchery x day	0.000	0.000	0.000	0.000	0.001	0.000	0.870	0.103	0.515
Hatchery x trt x day	0.831	0.472	0.000	0.000	0.655	0.854	0.647	0.627	0.025

TABLE 6.—Mean (SE) values and associated *P*-values from analysis of variance (last three columns) of stocking and harvest variables from 30 channel catfish ponds managed under conservative or liberal water use regimen at the A. E. Wood (AEW), Dundee (DFH), and Possum Kingdom (PKFH) fish hatcheries in 2010.

	Hatchery			Treatment		*P*-value		
Variable	AEW	DFH	PKFH	Liberal	Conservative	Hatchery	Treatment	Hatchery x Treatment
				Stocking				
Pond size (ha)	0.4 (0.0)	0.41 (0.0)	0.28 (0.01)	0.36 (0.02)	0.37 (0.02)	0.000	0.867	0.972
Number of fish	8,635 (22)	8,869 (300)	6,093 (249)	7,853 (395)	7,879 (367)	0.000	0.925	0.980
Density (fish/ha)	21,588 (54)	21,631 (730)	21,491 (503)	21,584 (456)	21,555 (362)	0.983	0.964	1.000
Fish length (mm)	90 (0.8)	89 (0.8)	89 (0.8)	89 (0.7)	90 (0.6)	0.516	0.271	0.697
Fish weight (kg)	49 (1.0)	47 (0.9)	32 (1.7)	43 (2.3)	43 (2.2)	0.000	0.781	0.979
Biomass (kg/ha)	123 (2.6)	114 (2.1)	114 (2.8)	116 (2.2)	117 (2.4)	0.033	0.780	0.973
Fish size (fish/kg)	176 (4)	191 (9)	189 (4)	186 (5)	185 (5)	0.206	0.847	0.990
				Harvest				
Number of fish	7,610 (181)	7,546 (331)	5,728 (295)	6,786 (316)	7,136 (321)	0.000	0.266	0.162
Density (fish/ha)	19,025 (454)	18,404 (808)	20,151 (628)	18,791 (579)	19,595 (502)	0.148	0.269	0.129
Fish length (mm)	264 (2)	258 (2)	238 (1.5)	253 (3)	253 (3)	0.000	0.860	0.596
Fish weight (kg)	1,386 (64)	946 (52)	631 (21)	1,008 (100)	967 (82)	0.000	0.431	0.028
Biomass (kg/ha)	3,465 (161)	2,307 (127)	2,242 (91)	2,750 (211)	2,592 (145)	0.000	0.250	0.027
Fish size (fish/kg)	5.6 (0.3)	8.1 (0.2)	9.1 (0.4)	7.3 (0.5)	7.9 (0.5)	0.000	0.114	0.194
Survival (%)	88.1 (0.02)	85.9 (0.05)	93.7 (0.02)	87.5 (0.03)	91.0 (0.02)	0.149	0.399	0.313
Growth (mm/d)	2.1 (0.03)	1.7 (0.06)	1.7 (0.04)	1.8 (0.07)	1.9 (0.05)	0.000	0.058	0.262
Feed fed (kg/ha)	3,899 (154)	2,576 (56)	2,004 (31)	2,963 (258)	2,689 (181)	0.000	0.004	0.010
Feed conversion	1.2 (0.03)	1.3 (0.11)	1.1 (0.03)	1.3 (0.08)	1.2 (0.02)	0.225	0.116	0.122
Mortality/pond	24 (11)	102 (57)	2 (1)	69 (39)	16 (9)	0.013	0.122	0.112
Culture days	82 (2)	100 (4)	90 (3)	94 (4)	87 (2)	0.001	0.048	0.190

TABLE 7.—Mean (SE) values and associated *P*-values from *t*-test of stocking and harvest variables from 30 channel catfish ponds managed under conservative or liberal water use regimen at the A. E. Wood (AEW), Dundee (DFH), and Possum Kingdom (PKFH) fish hatcheries in 2010.

	Fish hatcheries								
	A. E. Wood			Dundee			Possum Kingdom		
Variable	Conservative	Liberal	*P*-value	Conservative	Liberal	*P*-value	Conservative	Liberal	*P*-value
Stocking									
Pond size (ha)	0.40 (0)	0.40 (0)	1.000	0.41 (0)	0.41 (0)	1.000	0.29 (0.014)	0.28 (0.019)	0.870
Number of fish	8,633 (39)	8,638 (24)	0.909	8,858 (396)	8,879 (497)	0.975	6,146 (355)	6,041 (388)	0.848
Density (fish/ha)	21,582 (97)	21,595 (60)	0.909	21,606 (966)	21,655 (1,211)	0.975	21,479 (657)	21,502 (842)	0.983
Fish length (mm)	90 (1.2)	90 (1.2)	1.000	90 (1.2)	88 (1.1)	0.484	90 (0.9)	88 (1.1)	0.219
Fish weight (kg)	49 (1.6)	49 (1.5)	0.995	47 (1.6)	46 (1.0)	0.717	33 (2.2)	32 (3.0)	0.870
Biomass (kg/ha)	123 (4.0)	123 (3.7)	0.995	115 (3.8)	113 (2.4)	0.717	114 (4.3)	113 (4.1)	0.879
Fish size (fish/kg)	176 (5.4)	176 (5.4)	1.000	190 (13.9)	193 (12.8)	0.904	188 (3.2)	190 (6.6)	0.807
Harvest									
Number of fish	7,463 (257)	7,757 (267)	0.450	8,128 (303)	6,963 (481)	0.081	5,816 (465)	5,639 (415)	0.783
Density (fish/ha)	18,657 (643)	19,393 (667)	0.450	19,825 (739)	16,982 (1,174)	0.081	20,304 (1,154)	19,997 (656)	0.824
Fish length (mm)	264 (2.6)	263 (3.6)	0.765	256 (3.2)	259 (1.8)	0.369	238 (2.0)	237 (2.5)	0.754
Fish weight (kg)	1,286 (80)	1,486 (85)	0.126	1,025 (44)	867 (85)	0.149	591 (32)	672 (9.3)	0.060
Biomass (kg/ha)	3,215 (201)	3,714 (212)	0.126	2,499 (108)	2,115 (206)	0.149	2,063 (31)	2,421 (142)	0.065
Fish size (fish/kg)	5.9 (3.8)	5.3 (0.46)	0.370	8.0 (0.27)	8.2 (0.44)	0.681	9.8 (0.44)	8.4 (0.60)	0.094
Survival (%)	86 (2.7)	89 (2.5)	0.445	91 (3.8)	79 (7.3)	0.200	94 (2.8)	93 (2.4)	0.803
Growth (mm/d)	2.1 (0.01)	2.1 (0.05)	0.830	1.8 (0.04)	1.6 (0.09)	0.137	1.7 (0.06)	1.6 (0.06)	0.194
Feed fed (kg/ha)	3,560 (109)	4,238 (192)	0.015	2,520 (86)	2,633 (73)	0.349	1,988 (60)	2,020 (24)	0.623
Feed conversion	1.2 (0.03)	1.2 (0.05)	0.527	1.1 (0.02)	1.5 (0.2)	0.171	1.1 (0.04)	1.1 (0.04)	0.725
Mortality/pond	27 (23)	21 (8)	0.809	19 (16)	184 (106)	0.194	2 (1)	1 (1)	0.645
Culture days	83 (2)	82 (4)	0.858	93 (4)	106 (5)	0.076	87 (3)	93 (4)	0.217

TABLE 8.—Means (SE) values of consumption and cost (US $) of water used in channel catfish production ponds subjected to conservative or liberal water use treatment at three Texas Parks and Wildlife fish hatcheries in 2010.

Treatment	Acre-ft consumed	Pumping cost	Water cost	Total cost
		A. E. Wood[x]		
Conservative	6.2 (0.9)	113.19 (16.90)	680.37 (101.59)	793.56 (118.50)
Liberal	22.9 (1.8)	419.26 (32.18)	2,520.13 (193.45)	2,939.39 (225.61)
		Dundee[y]		
Conservative	7.4 (0.5)	N/A	961.86 (64.14)	961.86 (64.14)
Liberal	23.2 (0.3)	N/A	3,020.92 (43.10)	3,020.92 (43.10)
		Possum Kingdom[z]		
Conservative	1.2 (0.4)	N/A	50.87 (15.76)	50.87 (15.76)
Liberal	14.5 (1.6)	N/A	613.33 (65.96)	613.33 (65.96)

[x] Pumping cost based on $18.30 per acre-ft (R. Schmid, A. E. Wood Fish Hatchery, San Marcos, Texas, personal communication) and water cost based on $110/acre-ft (Guadalupe Blanco River Authority of Texas Annual Financial Report 2010; www.GBRA.org).

[y] Water cost based on $130.34/acre-ft (K. W. Miller, Wichita County Water Improvement District #2, Wichita Falls, Texas, personal communication).

[z] Water cost based on $42.35/acre-ft (Brazos River Authority FY2010 Annual Operating Plan. 2009; www.Brazos.org).

All website information accessed March 2011.

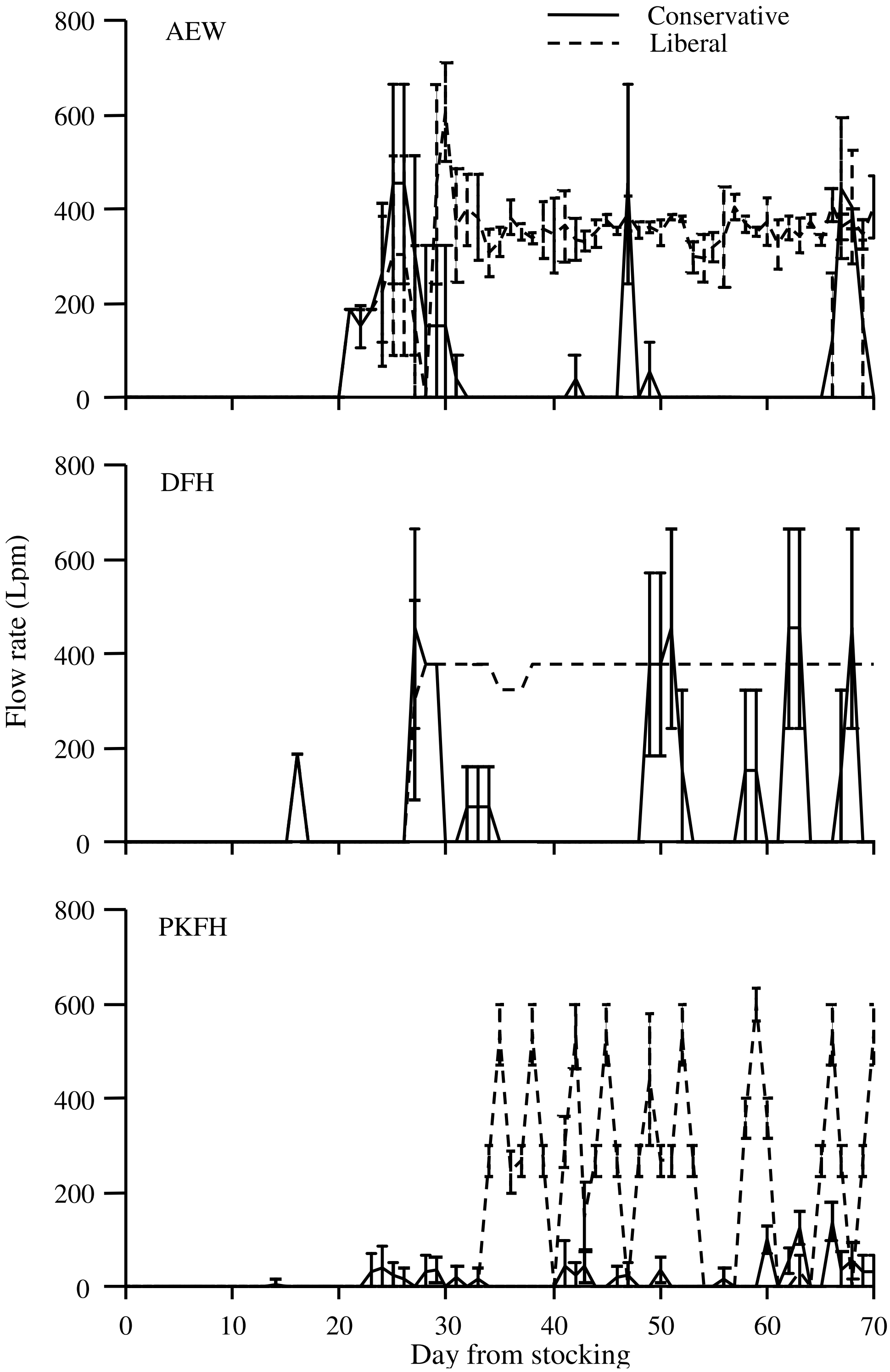

FIGURE 1.—Water flow rates in ponds at three Texas Parks and Wildlife fish hatcheries used to rear channel catfish fingerlings under conservative or liberal water use regimen in 2010. AEW is the A. E. Wood Fish Hatchery, DFH is the Dundee State Fish Hatchery, and PKFH is the Possum Kingdom State Fish Hatchery. Vertical bars are standard errors.

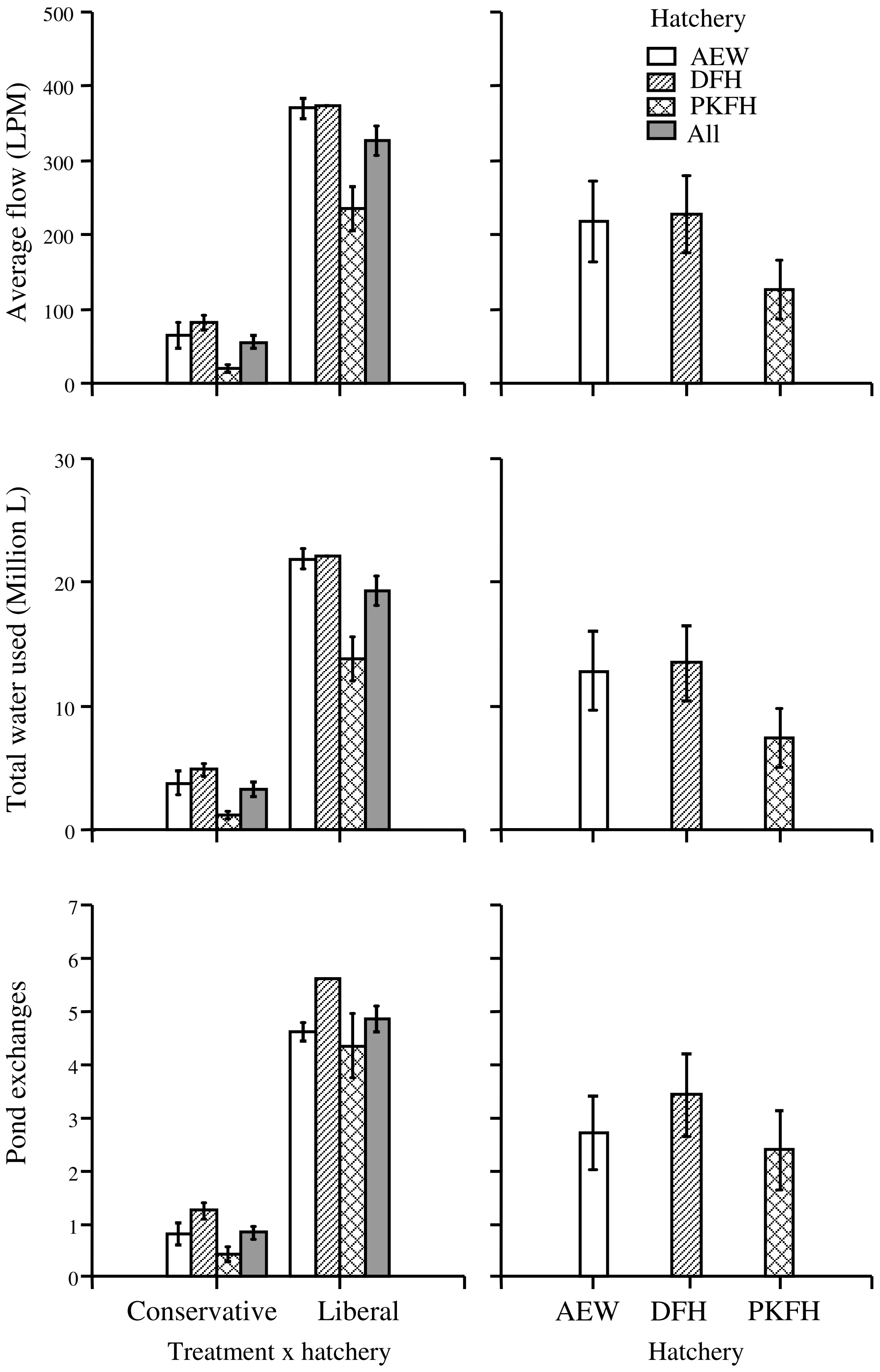

FIGURE 2.—Water use in ponds at three Texas Parks and Wildlife fish hatcheries used to rear channel catfish fingerlings under conservative or liberal water use regimen in 2010. AEW is the A. E. Wood Fish Hatchery, DFH is the Dundee State Fish Hatchery, and PKFH is the Possum Kingdom State Fish Hatchery. Vertical bars are standard errors.

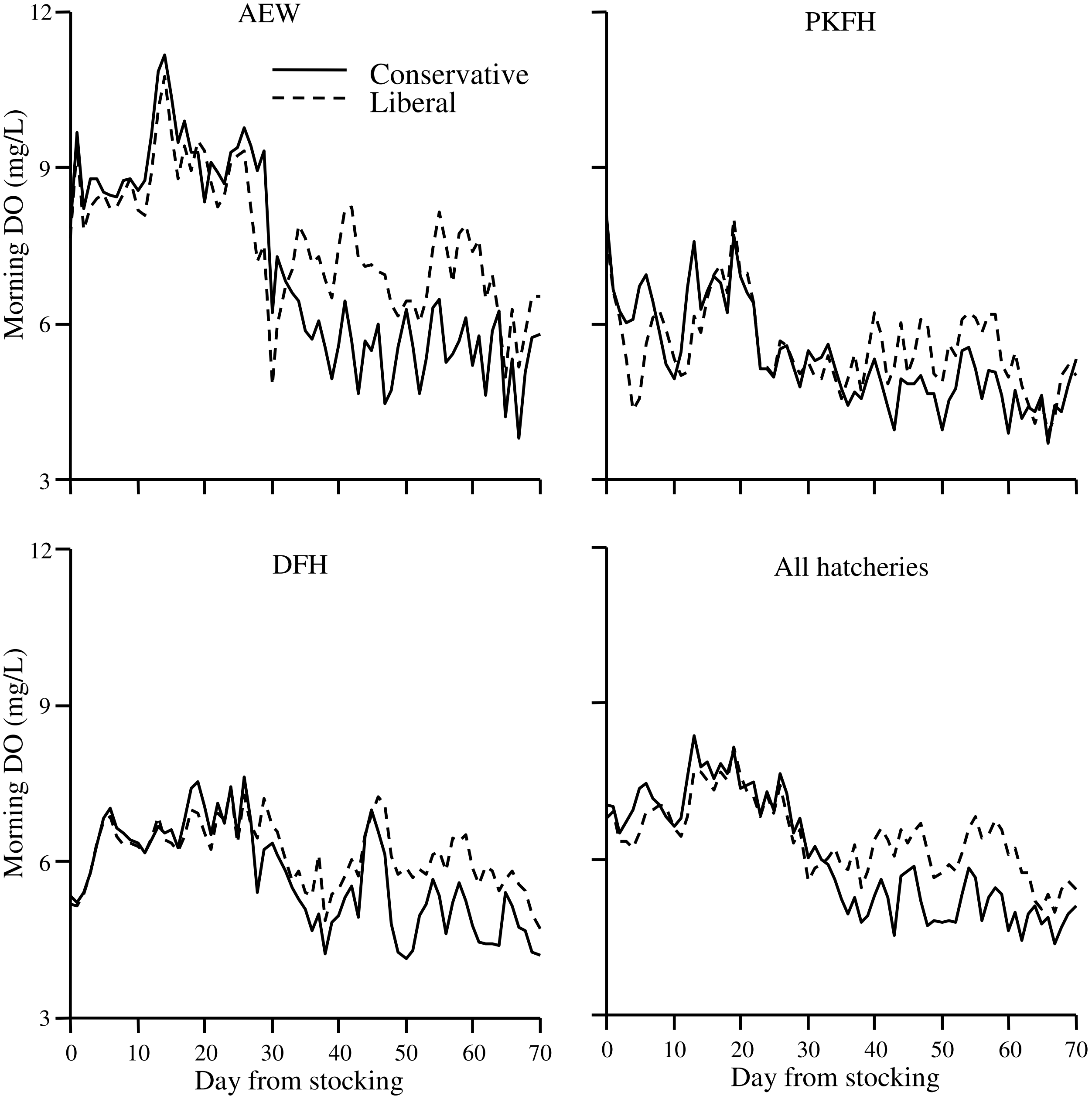

FIGURE 3.—Morning dissolved oxygen concentration trends in channel catfish fingerling rearing ponds subjected to conservative or liberal water management regimen at three Texas Parks and Wildlife fish hatcheries in 2010. AEW is the A. E. Wood Fish Hatchery, DFH is the Dundee State Fish Hatchery, and PKFH is the Possum Kingdom State Fish Hatchery.

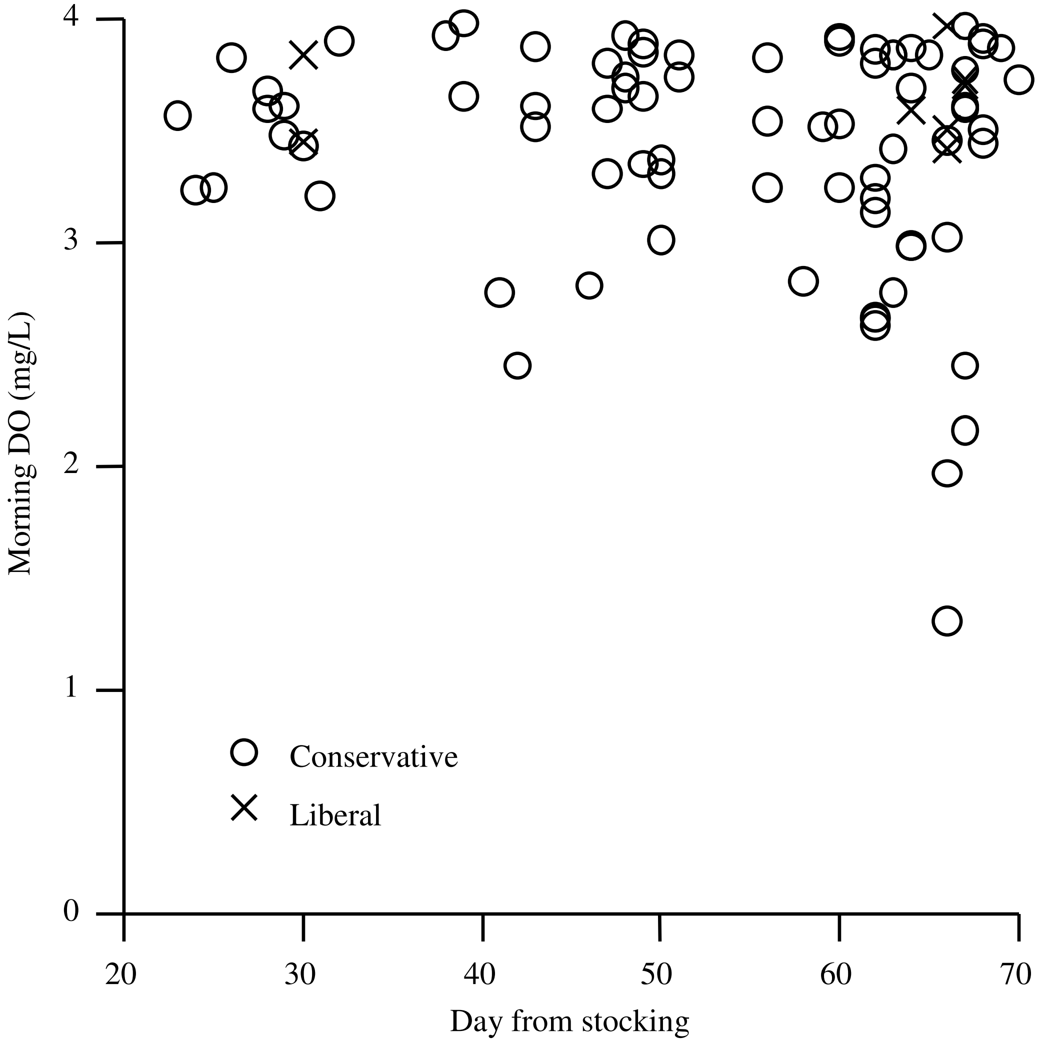

FIGURE 4.—Incidences of low dissolved oxygen concentrations (<4.0 mg/L) in channel catfish fingerling rearing ponds subjected to conservative or liberal water management regimen at three Texas Parks and Wildlife fish hatcheries in 2010.

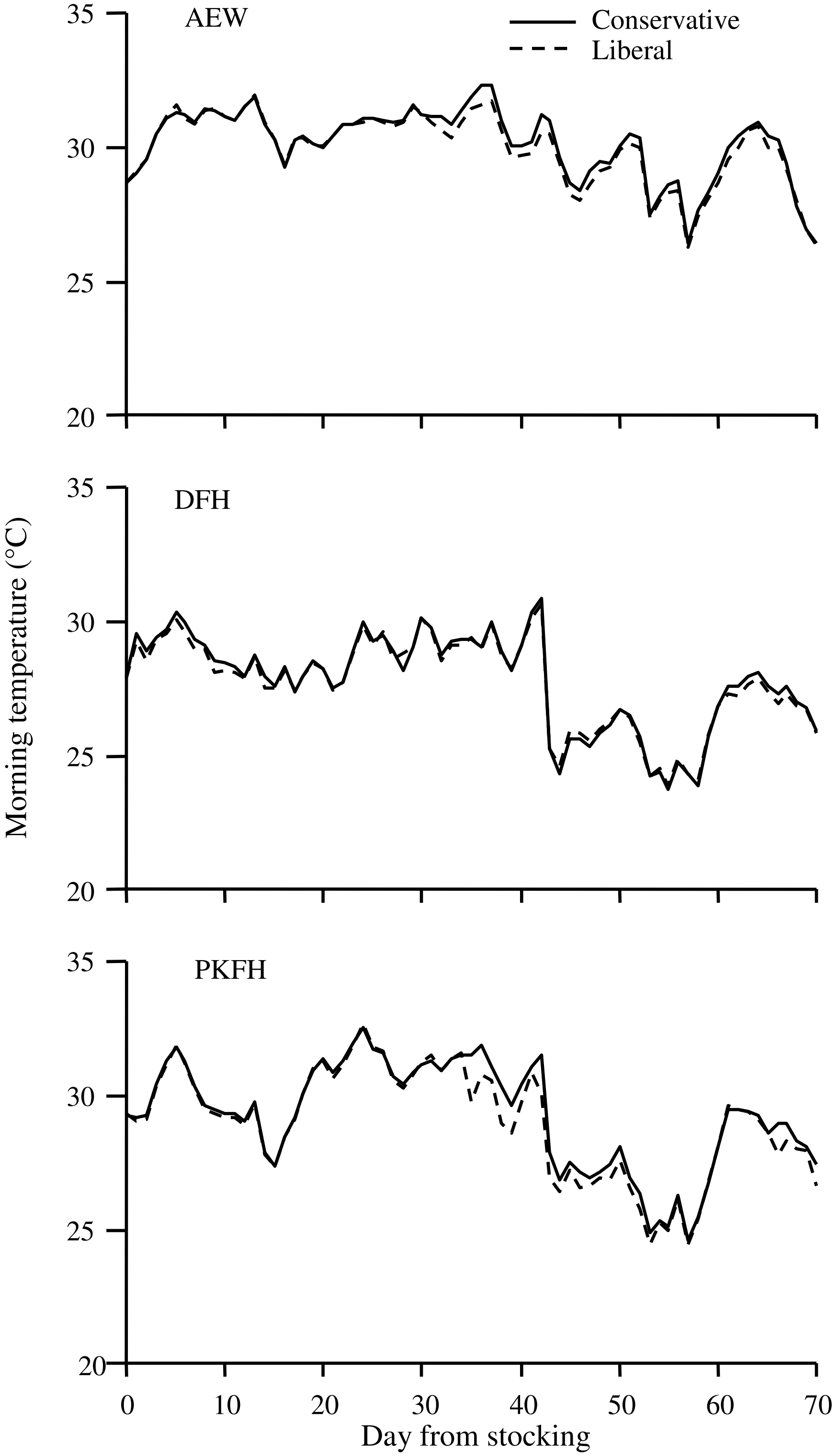

FIGURE 5.—Morning water temperature trends in channel catfish fingerling rearing ponds subjected to conservative or liberal water management regimen at three Texas Parks and Wildlife fish hatcheries in 2010. AEW is the A. E. Wood Fish Hatchery, DFH is the Dundee State Fish Hatchery, and PKFH is the Possum Kingdom State Fish Hatchery.

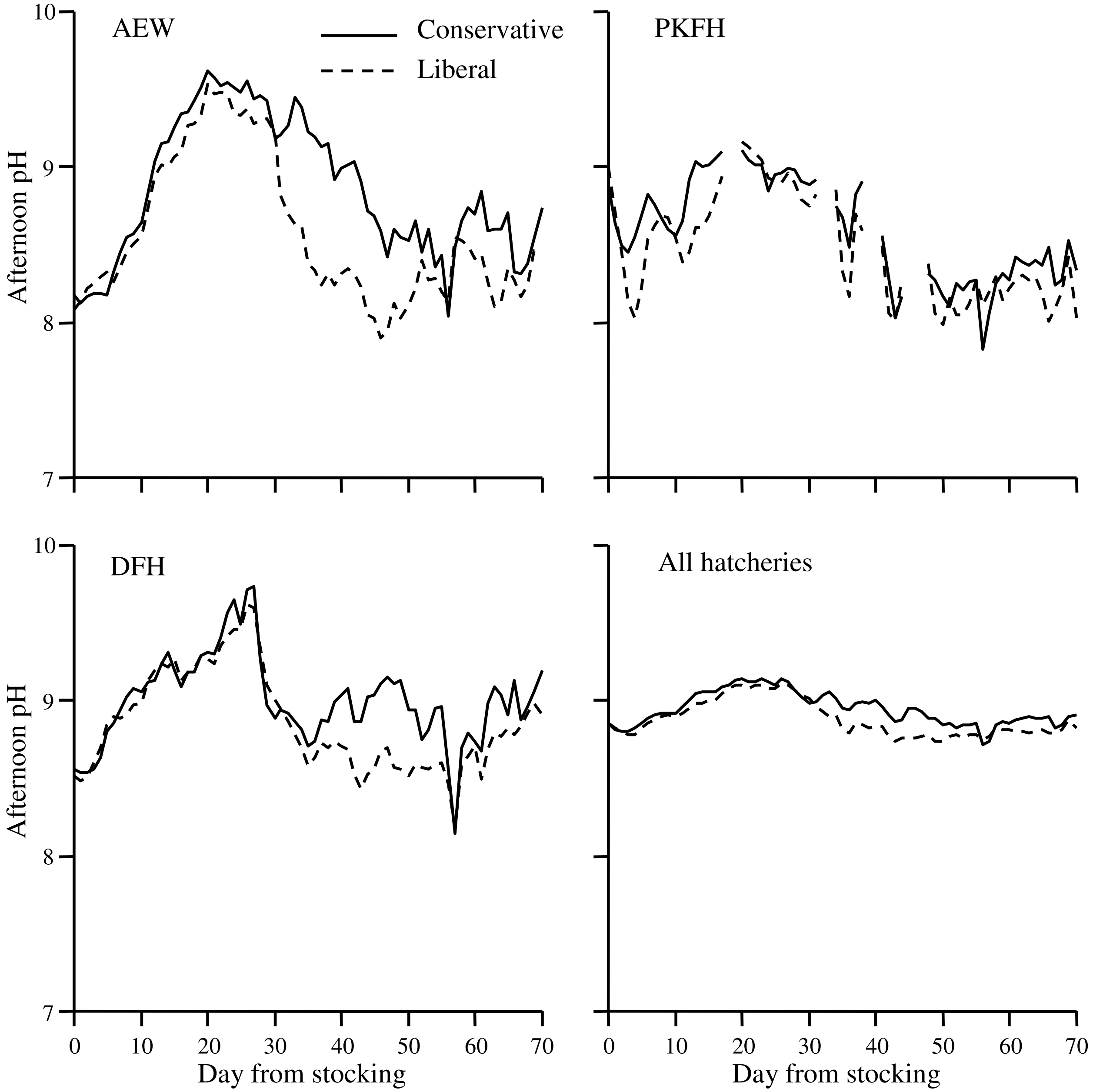

FIGURE 6.—Afternoon pH trends in channel catfish fingerling rearing ponds subjected to conservative or liberal water management regimen at three Texas Parks and Wildlife fish hatcheries in 2010. AEW is the A. E. Wood Fish Hatchery, DFH is the Dundee State Fish Hatchery, and PKFH is the Possum Kingdom State Fish Hatchery.

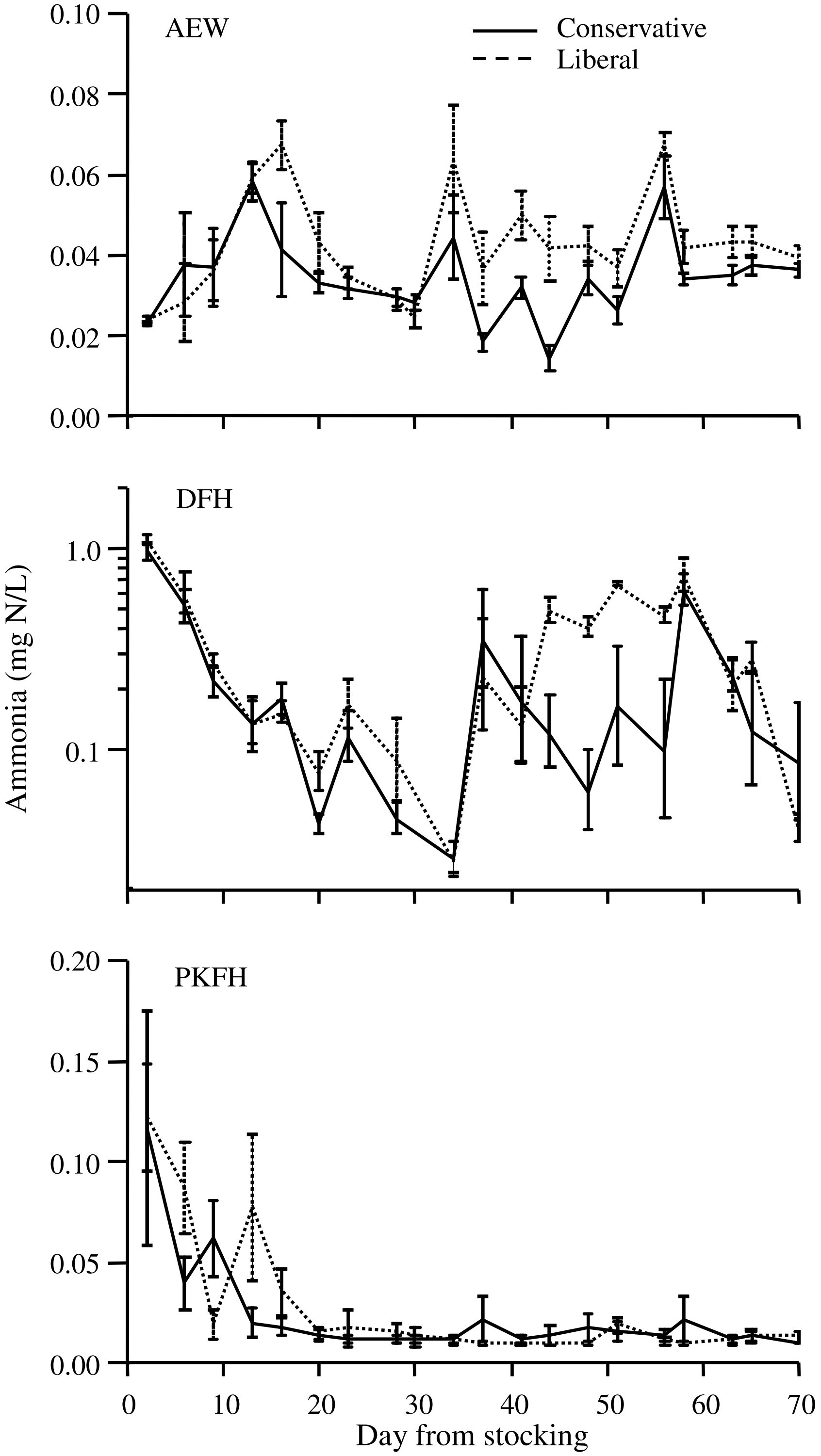

FIGURE 7.—Total ammonia nitrogen trends in channel catfish fingerling rearing ponds subjected to conservative or liberal water management regimen at three Texas Parks and Wildlife fish hatcheries in 2010. AEW is the A. E. Wood Fish Hatchery, DFH is the Dundee State Fish Hatchery, and PKFH is the Possum Kingdom State Fish Hatchery. Vertical bars are standard errors.

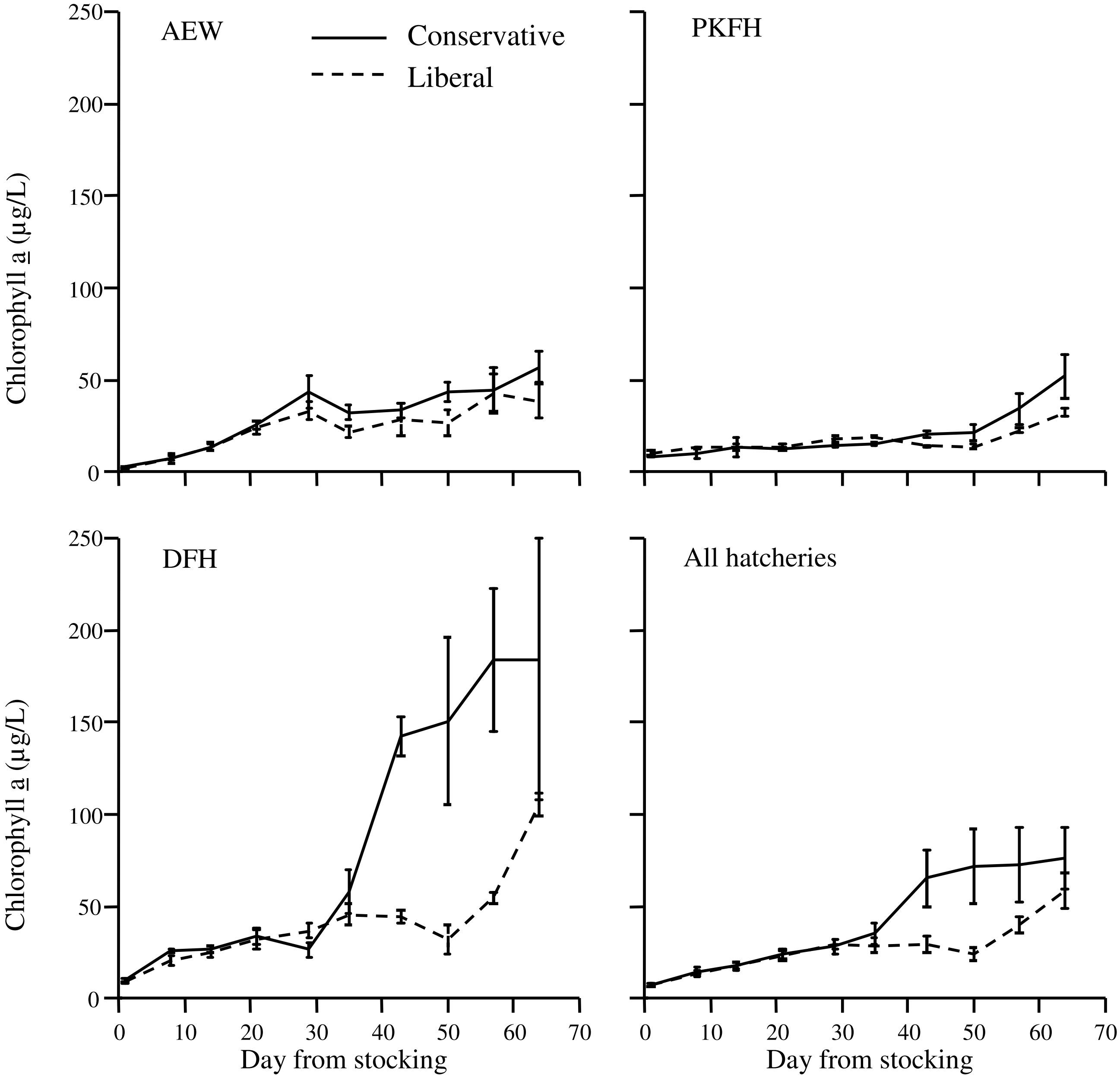

FIGURE 8.—Chlorophyll *a* trends in channel catfish fingerling rearing ponds subjected to conservative or liberal water management regimen at three Texas Parks and Wildlife fish hatcheries in 2010. AEW is the A. E. Wood Fish Hatchery, DFH is the Dundee State Fish Hatchery, and PKFH is the Possum Kingdom State Fish Hatchery. Vertical bars are standard errors.

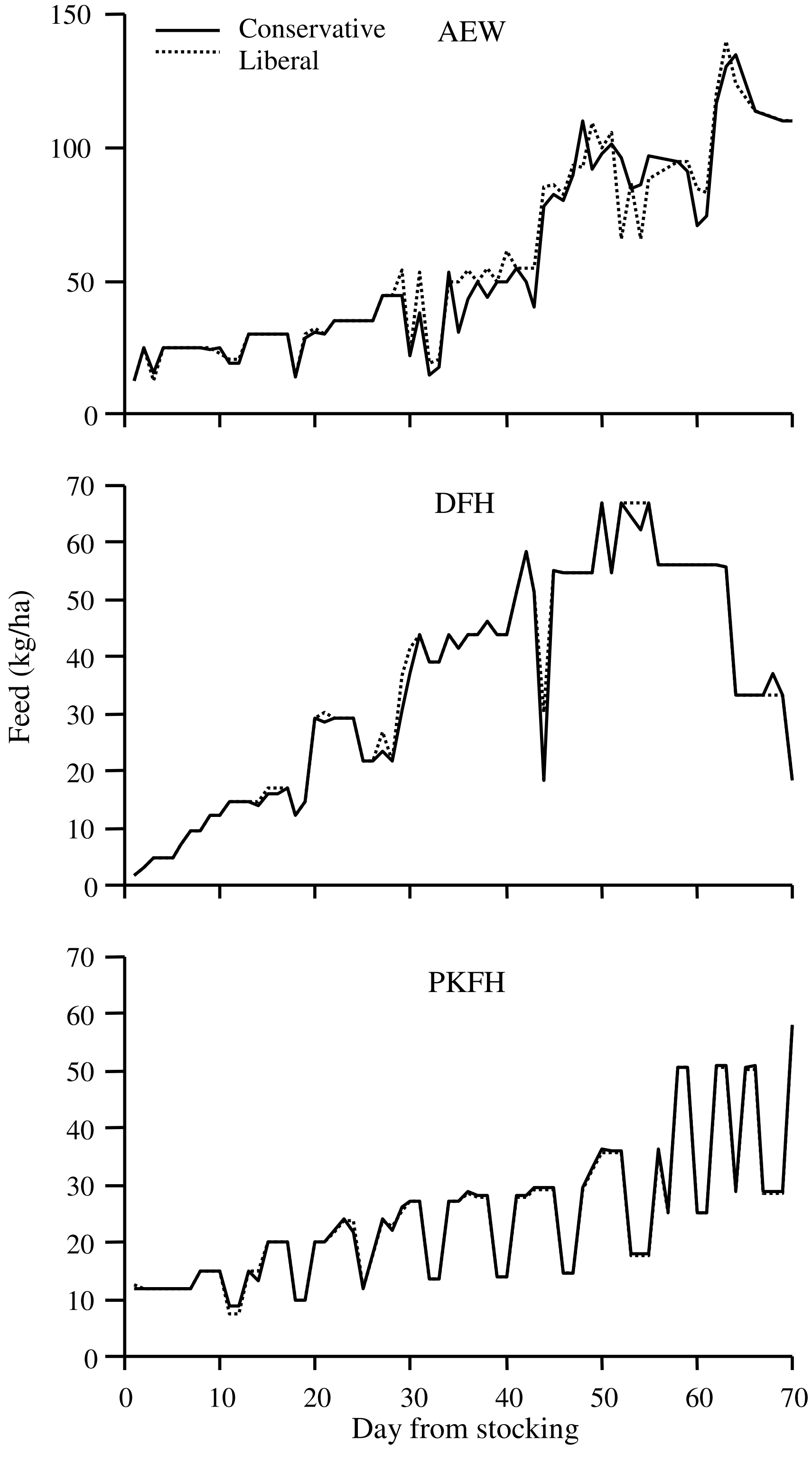

FIGURE 9.— Daily feeding rates (average weight fed kg/ha) used at three Texas Parks and Wildlife fish hatcheries to rear channel catfish fingerlings under conservative or liberal water use regimen in 2010. AEW is the A. E. Wood Fish Hatchery, DFH is the Dundee State Fish Hatchery, and PKFH is the Possum Kingdom State Fish Hatchery.

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