A Climate-Based Management Plan to Conserve Groundwater and Reduce Overflow in Aquacultural Ponds in the Southeastern U.S.

Charles L. Wax, Jonathan W. Pote, Thomas P. Cathcart

The potential for conservation of groundwater used in warm water aquaculture in the southern region is evaluated. Daily water balances for ponds are constructed by computing precipitation minus 0.8 * pan evaporation over a 40–year period (1961–2000) at five sites in the region: Fairhope, AL; Clemson, SC; Thompsons, TX; Stuttgart, AR; and Stoneville, MS.

Through computer simulation, daily water level fluctuations are controlled under two management schemes over the 40–year period: 1) pond surfaces are kept constantly at gage level by daily addition of sufficient groundwater to "make–up" evaporative losses not countered by precipitation, with excess precipitation lost to overflow; and 2) pond surfaces are allowed to drop six inches below gage level by cumulative evaporative loss not countered by precipitation, with addition of just three inches of groundwater at that point, leaving three inches of storage capacity for any subsequent excess precipitation. Amounts of groundwater used under the two management schemes are calculated and compared.

Under the "make–up" water use method, amounts used range from about 34–44 inches across the region, and average about 38 inches annually. Under the alternative "6/3" method of management, amounts used range from about 4–15 inches regionally, and average about 11 inches annually. Implied conservation potential from adoption of the "6/3" scheme ranges from 64%–88%, and averages 72% for the region.

Keywords: Climatological processes, groundwater, models

Introduction

Fish is considered a healthy food choice in developed regions and may provide the bulk of total protein intake in developing regions. World production and consumption of fish is geographically variable, but in 2004 over 30% of fish food consumed worldwide was provided by aquaculture (NMFS, 2004). In the U.S., 9% of seafood consumed is supplied by domestic aquacultural production of species such as tilapia, trout, striped bass, salmon, crawfish, oysters, and catfish. The U.S. aquaculture industry has expanded rapidly and has experienced substantial growth in the last ten years. Nationwide, aquacultural production increased from about 18 million tons in 1990 to over 32 million tons in 2004 (NASS, 2005).

Catfish is the predominant species produced, accounting for 46% of total U.S. aquacultural production, with U.S. catfish consumption (1.2 lbs/capita) ranking fifth behind shrimp, tuna, salmon, and pollock (NMFS, 2004). Four states in the southern region (AL, AR, LA, and MS) accounted for the overwhelming majority of this total national production (NASS, 2005). These four states accounted for 95% of the U.S. total of both surface water in aquaculture production in 2005 (170 million acres) and in value of sales in 2004 (over $480 million) (NASS, 2005).

The southern region has risen to prominence in the aquaculture industry largely because of its climatic characteristics. The humid subtropical climate of the region has temperate winters, evenly distributed rainfall through the year, and long, hot summers. With most places in the region receiving between 45 inches to 65 inches of precipitation annually, and with groundwater being relatively abundant and accessible across the region, water availability for aquaculture has been taken for granted. Recently, increased demand for groundwater, aggravated by a series of drought years, has prompted growing concern over future availability and quality of this vital natural resource, and the need for conservation of groundwater especially has become clear.

Agriculture is the major water consumer in the region, and aquaculture has the potential to become disproportionately consumptive. For example, most row crops in the region require 12-16 in/yr, whereas catfish farming requires up to 40 in/yr under current practices. In the "Delta" region of Mississippi where nearly 60% of U.S. farm raised catfish are produced, catfish production accounts for about 28% of all water used (Pennington, 2005). The production value of water used in aquaculture exceeds that of other food production methods. Boyd and Gross (2000) calculate the production value of water used for soybean production as $13/acre-in, compared to a value of $80/acre-in for catfish. As a valuable and fast-growing industry that requires large amounts of clean water, the future growth of warm water aquaculture requires that conservation methods for production be developed.

Another consideration is that processors of farm raised catfish prefer larger fish. Harvested fish increased in size from an average of 1.3-1.5 lb in the early 1990s to an average of 1.5-3 lb by the end of that decade (McGee and Lazur, 1998). Production of the larger fish requires a longer production cycle (almost five months more), increases production risks (8% increase in death loss), and increases production costs (McGee and Lazur, 1998). Additionally, prices for the fish are not increasing while prices of feed are rising. Only the most efficient producers will continue to make profits and stay in business. Any strategy that enhances conservation of groundwater and reduces production costs in this industry should be adopted.

A previous study (Pote, et al, 1988) showed that rainwater harvesting and storage was a promising groundwater conservation strategy in the aquaculture-intensive Delta region in Mississippi. The Extension Services in Alabama and Louisiana include variations of the "drop/add" strategy proposed by Pote, et al (1988) as industry best management practices for reducing effluent release in those states (Auburn University, 2002; LCES, 2003), but such recommendations remain largely unsubstantiated by research on a regional level. The best management scheme for this region would be one that would minimize pond overflow, capture rainfall and store it to offset evaporation losses.

This study evaluates the results of the techniques established by Pote, et al, (1988) for other locations in the southern region. The other locations were chosen to assess the effectiveness of the scheme throughout the region by taking into account the east-west precipitation gradient and the south-north change from maritime to continental characteristics. These spatial disparities produce minor climatic variations within the region that are potentially significant in their impacts on management strategies implemented to conserve water. This investigation develops climatological water budgets for ponds to evaluate these slight climatic differences.

Background Information

Commercial warm water aquaculture in the southern region is practiced in three types of ponds–watershed ponds, excavated ponds, and levee ponds. Levee ponds are most commonly used because their rectangular shape is convenient for management operations, and water levels can be controlled better than in other types of ponds (Boyd and Gross, 2000). These ponds are usually constructed on heavy clay soils with excellent water-holding capacity. A typical pond has about 17 acres of water on 20 acres of land, averaging about four feet in depth. Ponds are built with drains to control and adjust water level.

Although precipitation falling into ponds has the potential to supply up to 65" per year in some parts of the region, in practice nearly all this water is lost to overflow due to the management practice of holding pond levels at or near maximum. Levee ponds have virtually no watersheds, so sources of water other than surface runoff must be available. Because of water quality advantages, groundwater is presently by far the source of choice (EPA, 2004). Usually wells yielding 2000-2800 gal/min are adequate for four ponds of about seven water ha each (Wellborn, 1987). Theoretically the ponds can be operated indefinitely without draining. In practice, however, ponds are drained every two to 10 years for repair of levees.

Evaporation is a major and unavoidable water loss in the production process, because an open pond surface is necessary for gas exchanges as well as cultural activities such as feeding, aerating, and harvesting. Infiltration losses are minimal because leaking ponds are repaired or taken out of production in favor of better sites. Overflow losses are determined by both precipitation events and management practices.

In light of the above considerations, a realistic water budget for ponds can ignore surface water inflow and infiltration losses, but must account for precipitation and evaporation. Hydrologic modeling using historical meteorological records represents a method to assess rainwater storage in aquaculture ponds. In addition to the work by Pote, et al (1988), this approach has been used to determine effluent release from ponds in Mississippi (SRAC, 1998; Tucker, et al, 1996)) and as a tool for estimating pond requirements at individual facilities located in different geographical regions (Bolte and Nath, 1999).

Methods and Procedures

Site selection

Five sites were chosen for the analyses. Selection was based on one or more of the following three criteria:

1) sites were located in states that have significant aquacultural production;
2) sites had serially complete and homogeneous daily precipitation and evaporation records; and
3) sites were spatially dispersed to provide representation of the moister eastern and drier western portions of the region as well as the coastal (maritime) and interior (continental) characteristics of the regional climate.

Based on the best possible combination of these criteria, the following sites were selected: Thompsons, TX; Stuttgart, AR; Stoneville, MS; Fairhope, AL; and Clemson, SC. Figure 1 shows the location of each of these sites and demonstrates the P-E gradients that exist within this humid subtropical climate region.

Climatological Data

Daily observations of precipitation and evaporation for the period 1961 to 2000 were obtained from the National Weather Service Cooperative Observation System. The data were loaded into Excel spreadsheets for quality control and simulation analyses.

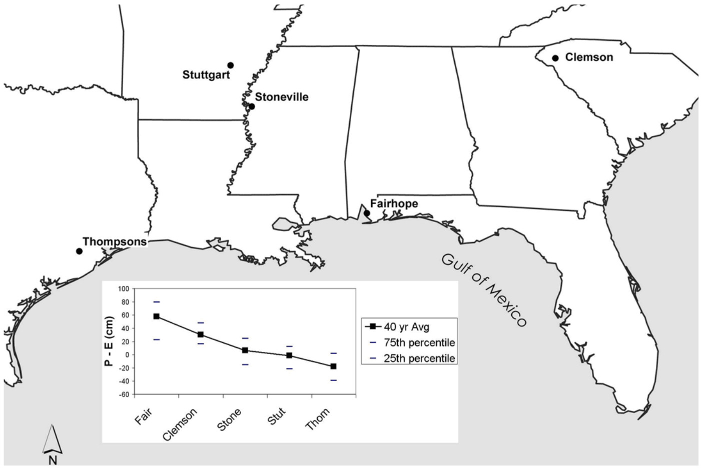

Figure 1. Location map illustrating regional P-E gradient.

While the precipitation data were essentially useful straight from the archived records, the evaporation data were much less complete and reliable (Irmak and Haman, 2003). In order to produce a complete daily evaporation record for each location, the existing daily observations were used to compute an average for each day. That average was then substituted where daily values were missing. Other errors appeared to be either typographical mistakes or excessively large values following long strings of missing observations, which were adjusted accordingly. If the observation in question appeared obviously wrong but no cause was readily evident, data from the next nearest location or the average value for that day was substituted. The result of this procedure, followed for all 40 years at all five locations, was a reasonably accurate and complete record of daily evaporation that could be used to quantify evaporative losses of water in the southern region.

Pan evaporation is not directly comparable to true evaporative loss from the surface of a lake or pond because of different heating characteristics and differing degrees of exposure to wind and sun of evaporation pans as compared to large bodies of water. Therefore, a "pan coefficient" is generally used to correct measured pan evaporation to a more realistic estimate of actual evaporative loss from ponds or lakes.

In early studies (Schwab, et al, 1955) a constant coefficient of about 0.7 was used to convert class A pan evaporation to an estimate of evaporation from large reservoirs. However, in more recent years it has been determined that the relationships vary from month-to-month and possibly from location-to-location (Kohler, et al, 1959; Ficke, 1972; Hounam, 1973; Yonts, et al, 1973; Linacre, 1994).

In a study conducted on a small, shallow pond near Auburn, AL, pan-to-pond coefficients were found to range from 0.72 in March to 0.90 in September, with an average of 0.81 for all months (Boyd, 1985; Boyd and Gross, 2000). This value is also consistent with work by Linacre (1994). Because the environment in which these coefficients were determined is closely related to the environments of aquacultural production ponds in the southeastern U.S., a correction coefficient of 0.8 was used in this study to correct the pan evaporation data to estimates of evaporative losses from ponds. Table 1 shows, for spatial comparison, the range of pond evaporation values thus determined from pan evaporation records for the five sites in this study.

Table 1. Summary of average daily pond evaporation rates during summer, southern region (range, in inches).

Site Location	Evaporation Rate Range (in inches)
Fairhope, AL	0.18 - 0.20
Clemson, SC	0.17 – 0.19
Stoneville, MS	0.20 – 0.24
Stuttgart, AR	0.20 – 0.24
Thompsons, TX	0.21 – 0.27

Pond Simulations

The water balance described above can be written:

$$\Delta V = P*A + Q_{in} - Ev*A - Q_{out}$$

where ΔV is pond volume change, P is precipitation, A is pond surface area, Q_{in} is volume of groundwater pumped, Ev is evaporation (0.8*class A pan evaporation), and Q_{out} is volume of pond effluent released. This balance can be rewritten:

$$\Delta E = P + Q_{in}/A - Ev - Q_{out}/A$$

with ΔE (cm), the change in pond elevation, replacing volume as the dependent variable and all terms converted for consistency of units.

Summation of the daily amounts of water added to ponds by precipitation and lost from ponds through evaporation provides an accounting of water level fluctuations resulting from climatic processes. Pumping and effluent release are intermittent events based largely on pond management decisions. Such a water balance approach is used here to assess the impact of climatic variability (seasonally, annually, and spatially) with the objective of determining the effectiveness of a management plan that takes advantage of regional climatic characteristics.

Simulations for an Infinitely Deep Pond
These simulations assumed $\Delta E = P - Ev$ (i.e., no pumping or effluent release) and were conducted to illustrate temporal availability of the precipitation resource for use in a "drop/add" rainwater storage scheme. A daily comparison of precipitation (P) and pond evaporation (0.8E) was conducted at each of the five locations for the 40-year period Jan. 1, 1961 - Dec. 31, 2000. Cumulative summation of these daily values provided seasonal and annual variations in precipitation availability.

For perspective, the daily elevations for the average year, the wettest year, and the driest year were singled out for each location. These years were not necessarily the same at each site. The average year was computed as the mean of the 40 P-0.8E values for each day through the year. The extreme years were analyzed using actual, not averaged, daily P-0.8E values for the years with the largest and smallest total precipitation, respectively. The daily water level patterns during these selected years at each site were then graphed by cumulative addition of daily P-0.8E values through each of the years.

This analysis shows the pond level regimes that might be expected from a purely climatological standpoint; that is, if the daily interaction between precipitation and evaporation were the sole factors in determining pond water levels, and if no water was added from any source other than precipitation, no overflow occurred, and no loss other than evaporation was encountered. Comparison of results at the five sites documents the regional variation in potential for precipitation to exceed pond evaporation on a cumulative, daily basis, and therefore indicates the comparative advantage of different areas within the region to use precipitation in a management scheme to keep ponds filled and thereby conserve groundwater.

Pond Water Management Simulations
Two approaches to pond water management were simulated. The first, in use in much of the pond aquaculture industry (Boyd and Gross, 2000), maintains ponds at the full mark (an arbitrary level "0" in the simulations) through addition of groundwater to replace water lost via evaporation. All precipitation is therefore lost as effluent release. This simulation represents a worst-case scenario and provides a basis for comparison with the second management approach, described below.

The second method is the "drop/add" scheme proposed by Pote, et al (1988), a management option in which the water level of the pond is allowed to drop 6" from the starting point before addition of any groundwater occurs. When groundwater is added, the amount is only enough to raise the level of the pond 3", leaving a 3" capacity to store any precipitation which might subsequently occur. Groundwater pumped is represented by the elevation increase (Q_{in}/A) required to fill the pond to –3" (recall that "0" is the arbitrary outflow elevation). Effluent release (Q_{out}/A) is calculated as any positive water elevation (i.e., E – 0 for all positive E's). When water is neither added via pumping nor lost via overflow, the water level of the pond fluctuates with positive or negative daily P-Ev values. The rainwater storage capacity of the pond using the "drop/add" approach is always present except when precipitation fills the pond to capacity.

The application of the two management systems was simulated using daily time steps for each of the five locations for the 40-year period 1961-2000. Water elevations for ponds at all five locations were calculated using the water balance described above, daily precipitation, and 80% of class A pan evaporation. Groundwater pumped and effluent lost was calculated and conservation of volume was observed.

Results and Discussion
Simulations for an Infinitely Deep Pond
Results from the cumulative analyses of the average year, the wettest year, and the driest year are shown in Figure 2. If all precipitation was captured and retained in the pond to offset subsequent evaporation, pond levels at all five sites during an average year would rise and remain above the starting level through about May 1st. In an average year, pond levels at all five sites end the year at or above the starting level for all but the western-most (Thompsons) and most interior (Stuttgart) locations. The worst case is an 8" drop at Thompsons.

Conceptually, these results document the regional climatic advantage available for aquaculture at these locations. The shapes of the average curves also reveal two other regional climatic traits relevant to management schemes for pond water levels. First, on the average, precipitation at all the sites is fairly evenly distributed through the year, so the shapes of the curves (sigmoid or double-sigmoid) are more dependent on the strong seasonality of evaporation. Secondly, two of the sites, Fairhope and Thompsons, show the marked effect of the tropical storm season on the average daily P-Ev.

Comparison of the wettest years at each of the five sites shows that the daily pond levels experienced a nearly continuous increase through those entire years at each location as precipitation exceeded evaporation most days of the year. The extreme wet years show the considerable differences in pond elevations as influenced by climate across the region. The Fairhope site ended its wettest year (1978) with pond levels 53" above the starting level while the Stuttgart site ended the wettest year there (1990) with water only 20" above the starting level– a regional range of 33".

Evaluation of the driest year at each of the five locations showed that pond water levels stayed near or above the starting level at all sites for the first two to five months of those years before starting to drop. Thereafter all sites showed a nearly continuous decrease in daily pond levels throughout most of the remainder of the year, as cumulative P-Ev remained consistently negative. Also, the extreme dry years exhibited almost as large a regional range of year-end water level as did the extreme wet years. For example, the Thompsons site ended its driest year (1988) nearly 33" below the starting level, but the Fairhope site ended the driest year there (1968) only 3" below the starting point – a range of 30".

A notable aspect of pond elevations that clearly emerged from this part of the analyses was the effect of wet and dry periods. Whereas major precipitation events dramatically and suddenly increased water levels, during dry periods the daily pond evaporation rates remained remarkably stable, damping the dramatic changes in water levels caused by precipitation. It was also noted that variability between the extreme wet and dry years was greatest at Thompsons and Fairhope, the two most coastal locations.

Water level fluctuations to the extent outlined above under a "climate control only" scheme cannot be tolerated in conventional warm water aquacultural ponds. Levees cannot economically be constructed high enough to allow for 56" to 33" changes in storage, the magnitude shown in Figure 2. Some degree of management must be introduced to control fluctuations in water level.

Pond Water Management Simulations

The results of the "make-up" management scheme are not illustrated in figures, since pond water elevations were constant throughout the simulations. Amounts of water added on a daily basis were small. They were only enough to replace daily evaporation.

The daily water level patterns created by the "drop/add" management scheme for the wettest years and the driest years at each of the five locations are shown in Figures 3 and 4. The days in the year when pond levels dropped to the 6"threshold (and 3" of groundwater was consequently added) are marked on the date of pumping in these Figures. The differences in the daily fluctuation patterns from place-to-place, the amounts of water added, and the distribution of pumping events through each of the years are evident in the Figures. These analyses illustrate the effects of rainfall, pumping, and evaporation on pond water levels, and document the capability of this management scheme when annual climatic variability is most extreme.

Figure 3 shows predicted daily water levels for the wettest years at all locations. Pond levels fell no more than 1-2" through April, and overflowed on many occasions with excess rainfall. Notably, the western-most and most interior locations began their wettest years with large deficits that were promptly made up by rainfall. No water had to be added at Fairhope, and only one pumping event was required at Clemson. The other three sites required only two or three additions of pumped water during the wettest year. Further-

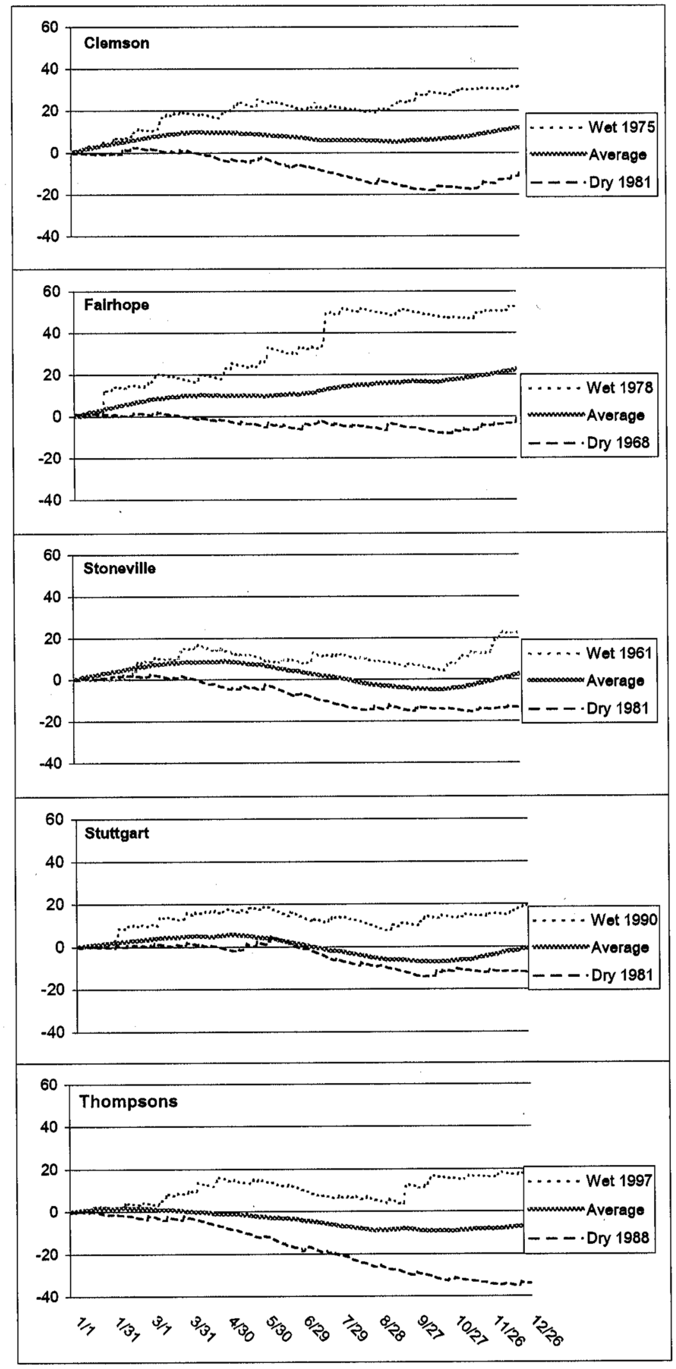

Figure 2. Daily water level determined by cumulative annual P-E, five locations–wettest and driest rears and 40-year average.

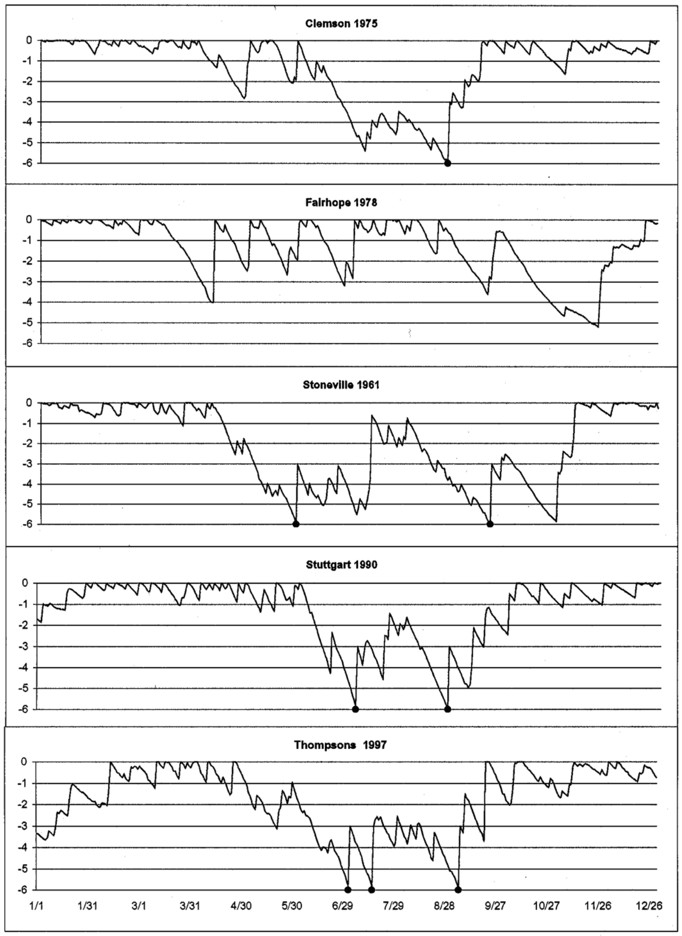

Figure 3. Daily water level, drop/add system, wettest years at each location.

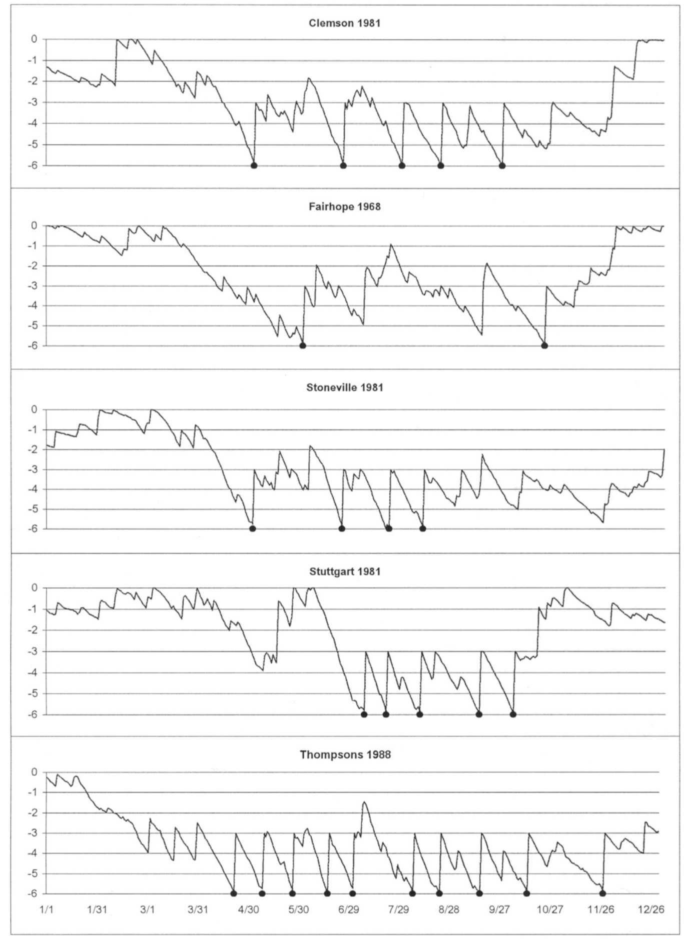

Figure 4. Daily water level, drop/add system, driest years at each location.

more, since only 3″ of water was added in those pumping events, subsequent large rainfalls at each of the sites were successfully captured. These simulations suggest that the climate in the Southern Region will provide nearly all the water necessary to maintain ponds within the 6″ design limit in wet years.

Figure 4 shows results of the management scheme in the opposite type of year–a year when rainfall was scarce and evaporation dominated. Water overflowed only one or two times through the year at all locations, and all locations required multiple additions of groundwater to maintain the pond levels within the 6″ design limit. Fairhope, the most coastal site, required only two pumping events, compared to 10 pumping events at Thompsons, the western-most site. The graph further reveals that, even in the extreme dry years, required pumping is limited to the time period between early April and late October. The comparative advantage of the maritime environment (Fairhope) is especially evident in the driest years. Figure 4 also clearly indicates how often 3″ additions of groundwater must be applied when no daily precipitation occurs, and thereby emphasizes the potential for conservation of this management method.

The years that required the most groundwater to maintain ponds within the 6″ design limit were typically those with the longest strings of dry days, rather than the driest years based on total precipitation. Figure 5 shows how the "drop/add" management strategy worked at Stoneville in 1966, the year requiring the most pumping events at that location (although 1981 was the driest year there). The addition of 24″ of groundwater (eight pumping events) was necessary. Pond level began dropping early in the year and no overflow occurred between mid-February and the last few days of the year. Repetitive additions of groundwater occurred at nearly uniform time intervals since no significant rainfall events took place during the part of the year when evaporation rates were consistently high. In comparison, the driest year (1981) was characterized by few major rainfall events but by multiple small events that occurred when water was most needed. The occurrence of periodic small rain events is historically more characteristic of the rainfall

Table 2. Forty-year averages of annual groundwater use (inches), two management methods, with conservation potential indicated

Test Site	"make-up"	"drop/add"	Amount Conserved
Fairhope	34.0	4.0	30.0 (88%)
Clemson	33.9	6.7	27.2 (80%)
Stoneville	40.1	14.5	25.6 (64%)
Stuttgart	39.7	13.5	26.2 (66%)
Thompsons	43.9	15.4	28.5 (65%)
Region	38.3	10.8	27.5 (72%)

regime in the Southern Region than are extended periods with no rain during the periods of greatest evaporative loss. This characteristic reveals that, even in dry years, there is a natural climatological advantage for the aquaculture industry in the South.

Table 2 compares water use under the "drop/add" scheme to the "make-up" water approach. Use of "make-up" water required a regional average of 38" of groundwater each year to keep ponds full. By comparison, the amount of groundwater required to keep ponds within the design limits of the "drop/add" scheme averaged about 11" a year regionally. These results indicate an average regional reduction in groundwater use of about 72% through employment of the "drop/add" management strategy. Specific figures for each site are given in the table.

Regional variation and spatial progression in both water use requirements and potential for conservation of groundwater are also evident in Table 2. For example, a pronounced regional east-west gradient occurred in the water required under the "drop/add" scheme at eastern-most Clemson (about 7") as compared to western-most Thompsons (about 15"). The maritime-to-continental gradient is also evident in the differences detected between the coastal environment represented by Fairhope (about 4") and the inland locations of Stoneville and Stuttgart (about 14-15" each).

Table 3, which shows the amounts of overflow calculated for both management schemes at each site, accentuates the efficiency of

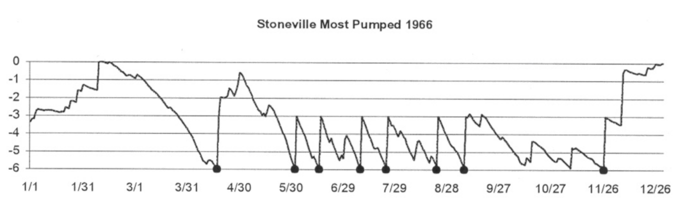

Figure 5. Daily water level 1966, drop/add system, year requiring most pumping, Stoneville, MS.

Table 3. Forty-year averages of annual overflow (inches), two management methods, with conservation potential indicated

Test Site	"make-up"	"drop/add"	Amount Conserved
Fairhope	56.5	26.5	30.0 (53%)
Clemson	45.8	18.7	27.1 (59%)
Stoneville	42.7	17.1	25.6 (60%)
Stuttgart	38.8	12.6	26.2 (68%)
Thompsons	36.8	8.3	28.5 (77%)
Region	44.1	16.6	27.5 (62%)

capturing rainfall rather than letting it escape to the environment. Use of the "make-up" water management scheme resulted in a regional average loss of 44" of useable precipitation each year. In contrast, the amount of useable precipitation lost to overflow when using the "drop/add" scheme averaged only about 17" per year regionally. These results thus indicate an average regional reduction in potentially-useable rainwater lost to overflow of about 62% through employment of the "drop/add" management strategy. Specific figures for each site are given in the table.

It is interesting to note that worst-case water use under the "drop/add" scheme was clearly superior to the best-case water use under the "make-up" scheme. Therefore, notwithstanding the spatial advantages of maritime environments or the temporal advantages of wetter years, the demonstrated potential for groundwater conservation is not limited by location in the region or by the annual climatic variability that is characteristic of the region.

Although the "drop/add" scheme is easily implemented and conceptually simple, there are some management considerations that must accompany its use. Although the 6" variation of water level was selected in part to minimize erosion of the levees, some protection and maintenance of exposed areas may be required. Also since in rainy years the primary source of water under this scheme will be rainfall, salinity levels should be monitored, especially after heavy rains. Finally, while it is unlikely that the water level fluctuations involved in the "drop/add" scheme will encourage increased benthic growth, if it becomes necessary to consider plans involving more extreme water level variations, deeper ponds may be necessary to maintain shading of pond bottoms.

Conclusions

It is becoming increasingly vital for warm water aquaculture producers to minimize production costs. Additionally, sustainable water use and avoidance of groundwater mining are conservation imperatives. Boyd and Gross (2000) state that reduction in effluent volume is the most effective way to save water in aquaculture production, and not only reduces water consumption but also reduces the pollution potential of pond aquaculture. Use of the suggested "drop/add" scheme has the potential to drastically reduce both groundwater use and loss to overflow in the southern region.

Pote, et al (1988) predicted a 50% reduction in groundwater use in catfish ponds in the Mississippi Delta. This investigation, using an expanded time frame and several locations throughout the southern region, concludes that actual reductions will exceed that 50% point at all sites in the region. The potential average conservation of groundwater indicated by this study ranges from 64% to 88%, and averages 72% regionally. Additionally, losses due to overflow were reduced from 53% to 77% regionally, with an average of 62%.

References

Auburn University, 2002. Auburn University and USDA/Natural Resources Conservation Service, Managing Ponds to reduce Effluent Volume, BMP No. 21. (http://efotg.nrcs.usda.gov.references/public/AL/G02ReduceEffluent.pdf)

Bolte, J.P. and S.S. Nath, 1999. In McElwee, K., D. Burke, M. Niles, and H. Egna (Editors), 16th Annual Technical report. Pond Dynamics/Aquaculture CRSP, Oregon State University, Corvallis, OR, pp. 183-84. (http://pdacrsp.oregonstate.edu/pubs/technical/16tch/8dssrla.pdf)

Boyd, C.E., 1985. Pond Evaporation. Transactions of the American Fisheries Society, 114:299-303.

Boyd, C.E. and A. Gross, 2000. Water Use and Conservation for Inland Aquaculture Ponds. Fisheries Management and Ecology, 7: 55-63.

EPA, 2004. Effluent Limitations Guidelines and New Source Performance Standards for the Concentrated Aquatic Animal Production Point Source Category; Final Rule. 40 CFR Part 451, Vol. 69, No. 162.

Hounam, C.E., 1973. Comparisons Between Pan and Lake Evaporation. World Meteorological Organization, Technical Note 126, 52 pp.

Irmak, S. and D.Z. Haman, 2003. Evaluation of Five Methods for Estimating Class Pan Evaporation in a Humid Climate. Horttechnology, 13(3): 500-508.

Kohler, M.A., T.J. Nordenson, and D.B. Baker, 1959. Evaporation Maps for the U.S. U.S. Weather Bureau Technical Paper 37, 13 pp.

LCES, 2003. "Aquacultural Production Best Management Practices (BMPs)", Pub. 2894 4/03 (Online only). Louisiana Cooperative Extension Service, Baton Rouge, LA.(http://www.agctr.lsu.edu/NR/rdonlyres/4005CC33-BF01-4FAB-8EA3-E2D9-ABCE038C/2616/pub2894aquaBMP6.pdf)

Linacre, E.T. 1994. Estimating U.S. Class-A pan evaporation from few climate data. Water International 19, 5 - 14

McKee, M.V. and C.E. Boyd, 1983. Evaluation of the Influence of Water Exchange in Channel Catfish Ponds. Transactions of the American Fisheries Society, 112: 557-560.

McGee and Lazur, 1998. "Alternative Opportunities for Small Farms: Catfish Production Review." University of Florida Cooperative Extension Service Fact Sheet RF-AC011. UF/IFAS, Gainesville, FL.

NASS, 2005. Catfish Production. National Agricultural Statistics Service, U.S. Department of Agriculture, July 27.

NMFS, 2004. Fisheries of the United States, 2004. Current Fishery Statistics No. 2004, National Marine Fisheries Service, Fisheries Statistics Division, NOAA, Silver Spring, MD.

Pennington, D., 2005. 2005 Annual Report, Yazoo Mississippi Delta Joint Water Management District, Stoneville, MS 38766.

Pote, J.W., C.L. Wax and C.S. Tucker, 1988. Water in Catfish Production: Sources, Uses, and Conservations. Special Bulletin 88-3, November 1988, Mississippi Agricultural and Forestry Experiment Station, Mississippi State, MS.

Schwab, G.O., R.K. Frevert, T.W. Edminister, and K.K. Barnes, 1955. Soil and Water Conservation Engineering, 3rd Ed., John Wiley and Sons, New York.

SRAC, 1998. Characterization and Management of Effluents from Aquaculture Ponds in the Southeastern U.S. SRAC Final Project No. 600, Southern Regional Aquaculture Center, Stoneville, MS. (http://aquanic.org/publicat/usda_rac/efs/srac/600fs.pdf)

Tucker, C.S., S.K. Kingsbury, J.W. Pote, and C.L. Wax. 1996. "Effects of Water Management Practices on Discharge of Nutrients and Organic Matter from Channel Catfish (Ictalurus punctatus) Ponds." Aquaculture 147 (1996) 57-69.

Welborn, T.L., 1987. Catfish Farmers Handbook. Mississippi Cooperative Extensive Service Publication 1549, 35 pp. Mississippi State, MS.

Yontes, W.L., G.L. Giese, and E.F. Hubbard, 1973. Evaporation from Lake Michie, N.C., 1961-1971. USGS Water Resources Investigations 38-73, 27 pp.

Corresponding Author:
Charles L. Wax, Professor and State Climatologist
Department of Geosciences
Mississippi State University
Phone 662–325–3915
Fax 662–325–9423
E–mail: wax@geosci.msstate.edu