Aquacultural Engineering 26 (2002) 277–289
aquacultural engineering
www.elsevier.com/locate/aqua-online

Design and development of a geothermal temperature control system for broodstock management of channel catfish *Ictalurus punctatus*

Steven G. Hall [a,*], James Finney [a], R. Paul Lang [b], Terrence R. Tiersch [b]

[a] *Department of Biological and Agricultural Engineering, Louisiana Agricultural Experiment Station, Louisiana State University Agricultural Center, 143 Doran, Baton Rouge, LA 70803, USA*

[b] *Aquaculture Research Station, Louisiana Agricultural Experiment Station, Louisiana State University Agricultural Center, Baton Rouge, LA 70803, USA*

Received 3 January 2002; accepted 29 July 2002

Abstract

A control system was designed to raise and maintain water temperatures within ~0.03-ha earthen ponds to a range conducive for spawning (24–30 °C) channel catfish *Ictalurus punctatus*. Heating was done during February 2001 to April 2001, when temperatures would have otherwise prohibited spawning (<24 °C). Temperature was increased from ~10 °C (ambient) by ~2 °C per day, and maintained at ~27 °C, by the addition of geothermally warmed water (~36 °C). The control system substantially increased the controllability and precision of heating ponds compared to manual operation. Systems were designed to control sets of four ponds. In designing this control system, consideration of biological constraints was essential. Reproduction in channel catfish is most strongly influenced by temperature. Because cold fronts are common during the winter and early spring (January–March), it was essential to ensure that pond temperatures did not fall below the range for spawning. Constraints on the heating rate and temperature variability to maintain fish health and stimulate spawning behavior were considered. Components of the control system included temperature measurement devices (type-T thermocouples), a central electronic control unit, electronic switches and electrically actuated ball valves. In response to the temperature sensed by each thermocouple,

* Corresponding author. Tel.: +1-225-578-1049; fax: +1-225-578-3492
E-mail address: shall@bae.lsu.edu (S.G. Hall).

PII: S0144-8609(02)00036-5

the controller sent a message to close or open the valve. When the valve was opened, warm water was added to the pond to increase the average pond temperature. Hardware and algorithm design and initial system testing were the major components of this project. The final design incorporated information on relevant biological parameters and safety features including peak pond temperature, independent aeration and water pressure control mechanisms. Initial results indicate successful control of this biological system, and ongoing studies suggest similar mechanisms may be used for additional control objectives. In particular, this system could be used to vary pond temperatures to study biological responses and to cool ponds by addition of well water during summer months.

Keywords: Channel catfish; Process control; Early spawning; Temperature; Broodstock

1. Introduction

Early spawning of channel catfish is of value for research, and, with development, could be used to improve natural and artificial spawning for commercial application. In order to improve research capabilities at the Louisiana State University Agricultural Center Aquaculture Research Station (ARS) using geothermal water (~ 36 °C), design of a control system was necessary to automate pond warming and to maintain temperatures for conditioning of male and female channel catfish, *Ictalurus punctatus* for artificial and natural spawning. Many geothermal resources exist in the west, but warm water is used for aquaculture applications in southern states including Louisiana, which used 43.9 TJ of geothermal energy in these applications in the year 2000 (Lund and Boyd, 2000). In designing this control system, consideration of biological and environmental constraints was essential. The desired criteria included warming of the ponds from ambient winter temperatures (as low as 4 °C) to the target temperature (27 °C) at a rate of ~ 2 °C per day to minimize stress to the fish. To optimize spawning, ponds needed to remain at 25-29 °C. Also, because cold fronts occur during this time, it was essential to maintain pond temperatures despite rapid fluctuations in air temperature (10–15 °C in 2–3 h).

Portable electronic control systems were designed for use with sets of four ~ 0.03 ha earthen ponds. Each system consisted of a temperature measurement device (type-T thermocouple), a central electronic data acquisition and control system, control software, and mechanisms for operating automated valves to allow the appropriate volume of warm water to be administered to heat the ponds. Previous work (Lang, 2001) showed the ponds to be well mixed by the aerators that were run constantly during heating. As a consequence, a single thermocouple placed in the middle provided a good estimate of overall pond temperature. The controllers were programmed to control temperature through a feedback system. It was also desirable to integrate control, monitoring and data recording capabilities within the same device. Therefore, each controller had multiple input and output channels and acted as a data logger. A display allowed the user to monitor temperature data at the pond bank. Data were downloaded to a portable computer.

The final design incorporated information on relevant biological parameters and safety features including peak pond temperature and water-pressure control mechanisms. Background information on the biology of channel catfish was utilized to design hardware and software to provide optimal conditions for egg production. One set of four ponds was used for further testing of variations in programming to verify temperature control limitations. This controller was later used to control temperature by addition of cold water during the summer. Detailed information on the biology, design, construction and testing of the system is presented below.

2. Biology of channel catfish

2.1. General reproductive biology

The channel catfish is the most important cultured food fish in the United States, with a harvest of more than 600 million pounds in 2000 (USDA, 2000). The most common method of producing channel catfish is in ponds, where mature broodfish are provided with spawning containers that simulate natural nesting sites chosen by the male (Clapp, 1929). The males attract females to the containers (e.g. metal drums, boxes or milk cans) where spawning takes place. The male then drives the female away and cares for the egg mass (Huner and Dupree, 1984; Steeby, 1987). The eggs, which form an adhesive mass, can be removed by hand and incubated in hatcheries with the fry, to be reared later to market size in grow-out ponds. Although spawning may continue through August in some regions, most commercial operations in the southeastern United States collect egg masses from May through July (Tucker and Robinson, 1990). The current practice of producing channel catfish in ponds has been used for more than 70 years (Huner and Dupree, 1984). At present, the channel catfish industry relies exclusively on pond spawning to produce fry and fingerlings for grow-out.

Spawning of channel catfish occurs annually when water temperatures range from 24 to 30 °C and ceases when water temperatures remain above 30 °C (Brauhn, 1971; Davis et al., 1986; MacKenzie et al., 1989). Thus, under normal conditions, production of channel catfish is limited to the late spring and early summer, and is affected by weather conditions such as cold fronts (which are common during the spring) that can interrupt spawning (Huner and Dupree, 1984). However, channel catfish can be induced to spawn 1–2 months before the onset of the normal season through the supplemental heating of broodstock ponds, when temperatures would otherwise be prohibitive (Lang, 2001). The early spawning of channel catfish could increase the annual availability of fingerlings and fry, allowing producers and researchers more flexibility in their operations.

2.2. Temperature effects on channel catfish reproduction

The channel catfish follows an annual cycle of reproductive development (Brauhn and McCraren, 1975; Davis et al., 1986; MacKenzie et al., 1989). The reproductive

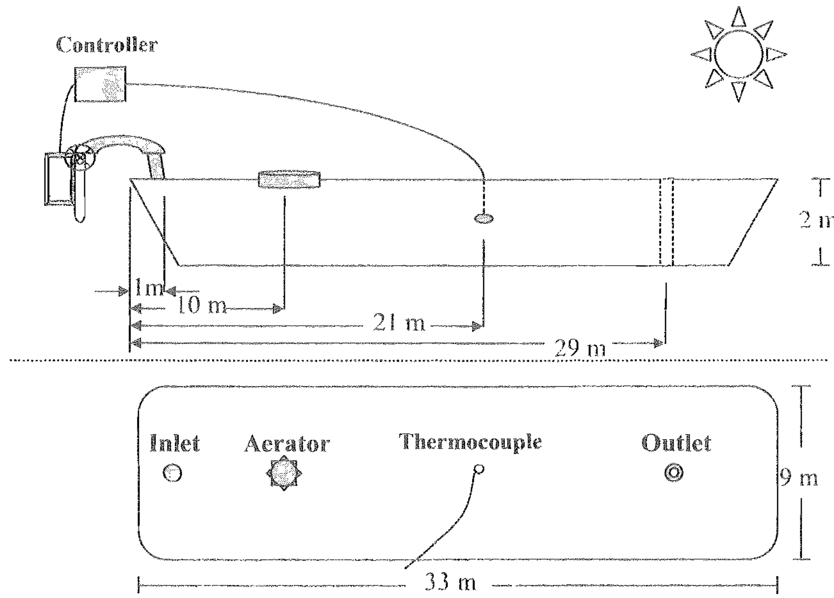

Fig. 1. The pond inlet allowed geothermally heated water to enter the pond via the controlled valves. Mixing and aeration were performed by the aerator, and the thermocouples were located to measure the temperature of mixed water.

state of the gonads, represented by the gonadosomatic index (GSI = gonad weight divided by body weight × 100) advances throughout the winter and into the spring, in preparation for spawning. Following spawning, GSI decreases to a minimum seasonal value, and maturation begins again. Temperature appears to be the primary factor that influences this seasonal pattern in GSI and the timing of spawning in channel catfish (Davis et al., 1986). Although reproduction in channel catfish is ultimately a result of an internal hormonal cycle, the magnitude of changes in GSI is most strongly influenced by ambient temperature. Therefore, in the early induction of pond spawning of channel catfish, it is necessary to maintain pond temperatures within the range of 24–30 °C to prevent regression of the gonads and cessation of spawning activity. Likewise, to delay spawning (Brauhn, 1971), it is necessary that pond temperatures remain below the range conducive to gonad maturation.

3. Methodology

Design of this temperature control system was based on the biological background information described above. Engineering design focused on hardware, including measurement devices, wiring, electrically actuated polyvinyl chloride (PVC) ball valves and software that encoded control algorithms. Finally, a series of trials was used to evaluate the system components and to confirm and clarify operational characteristics and biological results. Our objectives were: (1) hardware design, (2) software design, (3) system construction and (4) component and system testing.

3.1. Pond description

Study ponds were 33 m long and 9 m wide, with an average depth of 2 m (Fig. 1), with an inlet on one end for warm water (15-cm diameter line, 10-cm diameter automated valves). Aerators were situated 10 m from the inlet along the centerline of the pond and were operated continuously during inflow to fully aerate incoming well water. Thermocouples were located 21 m from the inlet along the centerline to measure water temperature after mixing by the aerators. The outlet maintained pond depth by use of a 10-cm PVC standpipe and was located 29 m from the inlet.

The pump used to provide the heated water in this case had significant energy costs. A 40-HP motor rated at 98 amps 220 V, three-phase for pumping from the deep geothermal well used 21.56 kW of electricity per hour. At a cost of \$0.08/kW-h, this amounted to \$1.72/h or \$13.80/day when run for 8 h daily. This was the case during the year 2001 (personal communication, R. Romaire, Director, ARS).

3.2. Hardware design

The existing facilities included a 700-m deep well which provided ~2400 l/min (lpm) of water at ~36 °C. This water had low hardness (< 100 ppm as $CaCO_2$) but was generally suitable for culture of channel catfish (Busch, 1985). Aeration was provided by use of mechanical rotary aerators during and after addition of warm water. The previous control method involved manual adjustment of 15-cm gate valves and temperature measurement using manual thermometer readings (Lang, 2001). The new system was designed to require less labor, offer more precise temperature control and more flexibility by use of software applicable to a variety of control mechanisms for various biological studies.

A datalogger (Campbell Scientific CR23X, Campbell Scientific Inc., North Logan, UT) was chosen as the central control unit. Characteristics important to this project included 24 analog input channels, eight control ports (±5 VDC), a robust instruction set familiar to the investigators and capacity to store over two million data points in battery-protected memory. A type-T (copper-constantan) thermocouple was constructed for each of four ponds that were controlled at a given time. The junction end was waterproofed with silicone and mounted in the pond opposite to the warm-water inlet and midway between the pond floor and water surface. The opposite end of each thermocouple was attached to a pair of analog input channels on the CR23X controller.

The original gate valve used to heat each of the four ponds was replaced with a 10-cm electrically actuated PVC ball valve (Model LB308; Hayward Industrial Products, Elizabeth, NJ). Although the valves could be manually operated, the handles were replaced by electric actuators (Model E153; Hayward Industrial Products). Application of 110 VAC to a pair of screw terminals on the actuator opened the valve. Similarly, application of 110 VAC to another pair of terminals closed the valve. The complete closing of the valve in this configuration required ~6 s, reducing sudden pressure changes in supply lines during actuation.

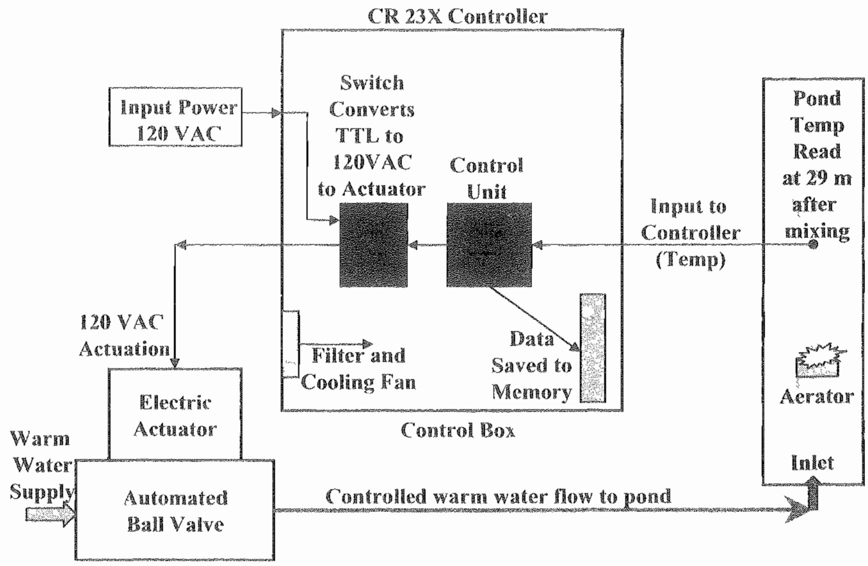

Fig. 2. The hardware used for the control system included thermocouples to measure pond temperature, a controller with data memory, switches, actuators and valves to maintain pond water at desired temperatures. Data were saved at regular intervals to a battery backup memory unit on the Campbell Scientific 23X controller (diagram not to scale).

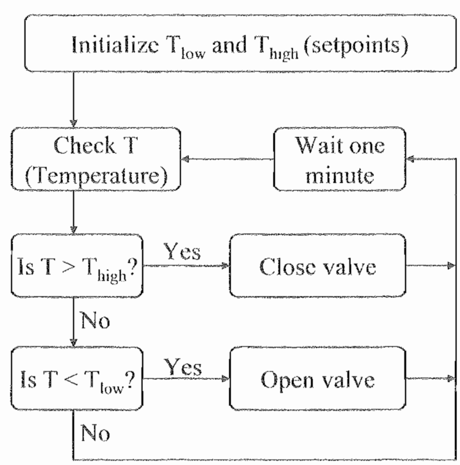

Fig. 3. The initial algorithm programmed into the Campbell Scientific CR23X controller maintained temperature between low and high temperature setpoints. Improved algorithms could include variable set temperatures and partial opening of valves.

Solid state relays (3-32VDC input/0.24-330VAC/10A output, model SNC-R2010-502, National Controls Corporation) were used to transfer control signals from the controller to the actuators. When the control unit switched the voltage of a control port to 5 VDC, the switch activated and closed the circuit on the 110 VAC side. Each pond required two switches: one to open the valve and one to close it (Fig. 2).

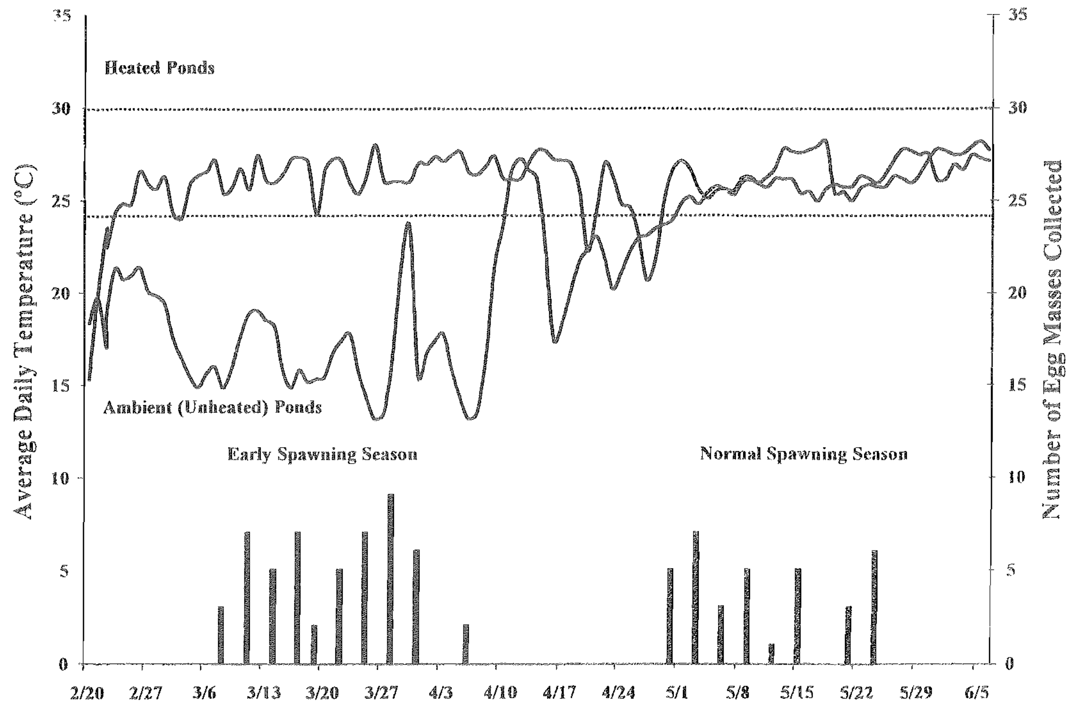

Fig. 4. Early spawning of channel catfish *I. punctatus* was successful in ponds heated manually with geothermal water. This data is representative of year 2000 results, showing a number of early spawns produced in March and April, as opposed to the normal season spawns starting in May. This data also shows temperature variations of manually controlled ponds of approximately ±4 °C.

3.3. Software design

The software design required consideration of valve actuation timing, wiring considerations, and biological and physical constraints. Each step of the control process was executed at 1-min intervals. First, the temperature of each pond was observed. Next, each pond temperature was compared to a desired minimum temperature (26 °C) and maximum temperature (27 °C). Conditional statements yielded one of three outcomes:

1) If the measured temperature was below the desired minimum, the valve was opened (or allowed to remain open) to add warm water.
2) If the measured temperature was above the desired maximum, the valve was closed (or allowed to remain closed) to prevent the addition of warm water.
3) If the measured temperature was between the limits, the valve remained in its current state.

Fig. 3 presents a flowchart of the control logic used for initial testing. Additional algorithms can be used for more complex control strategies. Each minute concluded with the recording of date, time and temperature values. The temperature of the datalogger wiring panel was used as a surrogate for air temperature, because this box

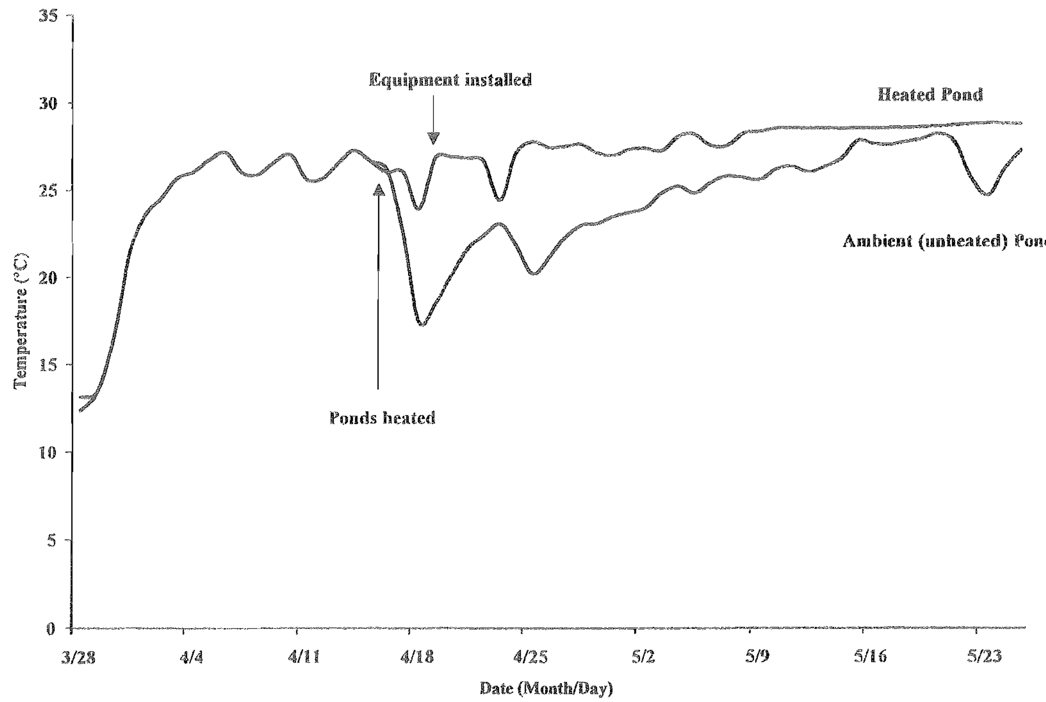

Fig. 5. Pond temperatures measured under ambient (no heated water added), and controlled conditions indicated improved controllability with the process control system during April and May 2001. Pond heating was begun using manual control on April 15, and automated temperature control commenced on April 25. Time scales differ between Figs. 4 and 5.

was protected from direct sunlight, but otherwise was open to the atmosphere. A copy of the CR23X program can be obtained from the corresponding author.

4. Results

4.1. System testing

The system was evaluated to determine temperature profiles under ambient conditions in Louisiana. Fig. 4 shows data collected from the system when operated manually. In this study, temperature control with the automated system (Fig. 5) was superior to that using manual operation of the valves. Heating curves showed typical first-order dynamics. Temperatures were controlled effectively at 27 ± 2 °C with this controller, compared with ± 3–5 °C variation when using manual control. In addition to the improved temperature control, automation greatly reduced the labor demands made by manual control. Heating rate was limited by ambient air temperature, wind characteristics, pond configuration and available water temperature and flow rate. With the available water flow ($\sim$2400 lpm) at 36 °C, the ponds heated at a maximum rate of $\sim$2 °C/h, well above the 2 °C/day required during heating. Water temperatures were held within ± 1 °C during most of the period

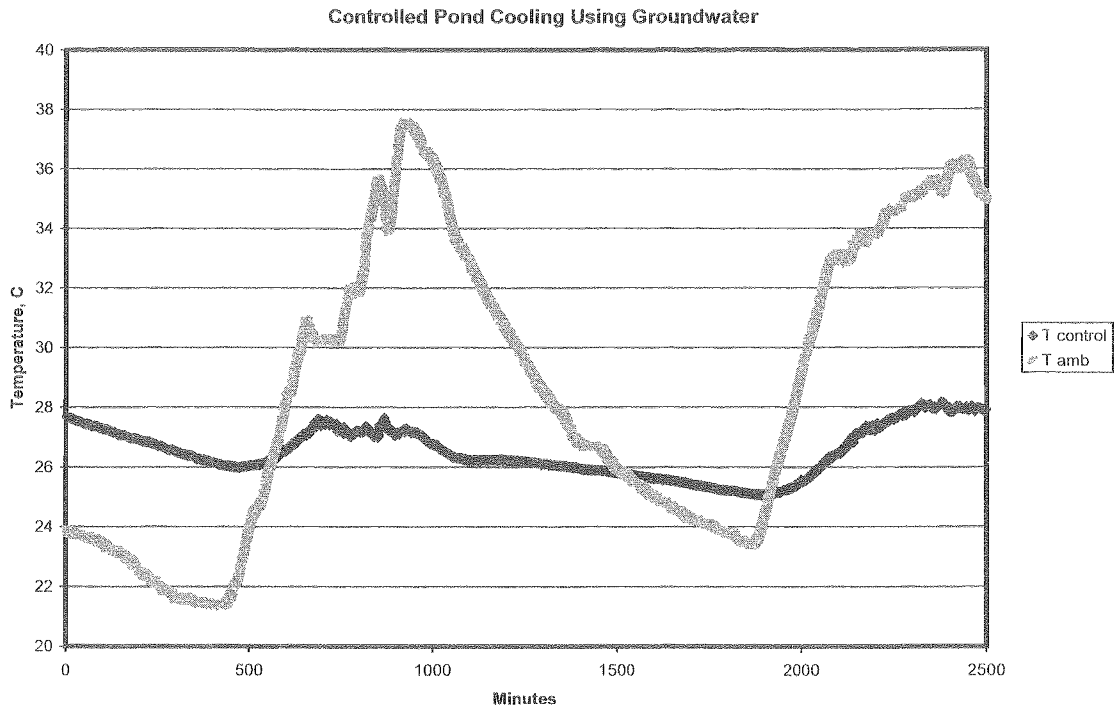

Fig. 6. Ambient air temperatures varied more than controlled water temperature while using groundwater to maintain temperatures for channel catfish to remain in spawning condition. Controlled pond temperatures varied between 25 and 28 °C, while ambient air temperatures varied between 21 and 38 °C.

shown in Fig. 5, compared to up to 10 °C variation in ambient water temperature during the same period.

4.2. Pond cooling

A similar system was mounted on one of the ponds to test the capability to cool ponds during summer weather. This capability was used to maintain channel catfish in spawning temperatures in the summer, so that later spawning would be possible. This test revealed that it was possible, using this system and available well water at approximately 22 °C to hold temperatures in the ponds at a level low enough to extend the spawning season despite ambient air temperatures as high as 38 °C (Fig. 6).

4.3. Other thermal strategies

Using automated valves, it was possible to maintain water temperatures of 27 ± 2 °C, which is within the optimum range for spawning of channel catfish. However, it is possible that channel catfish respond to more than mean static or fixed temperatures. In laboratory studies, channel catfish that were blinded and pinealectomized (thus receiving no stimuli other than temperature) had larger changes in gonad weight and higher GSI values under natural temperature regimes than did

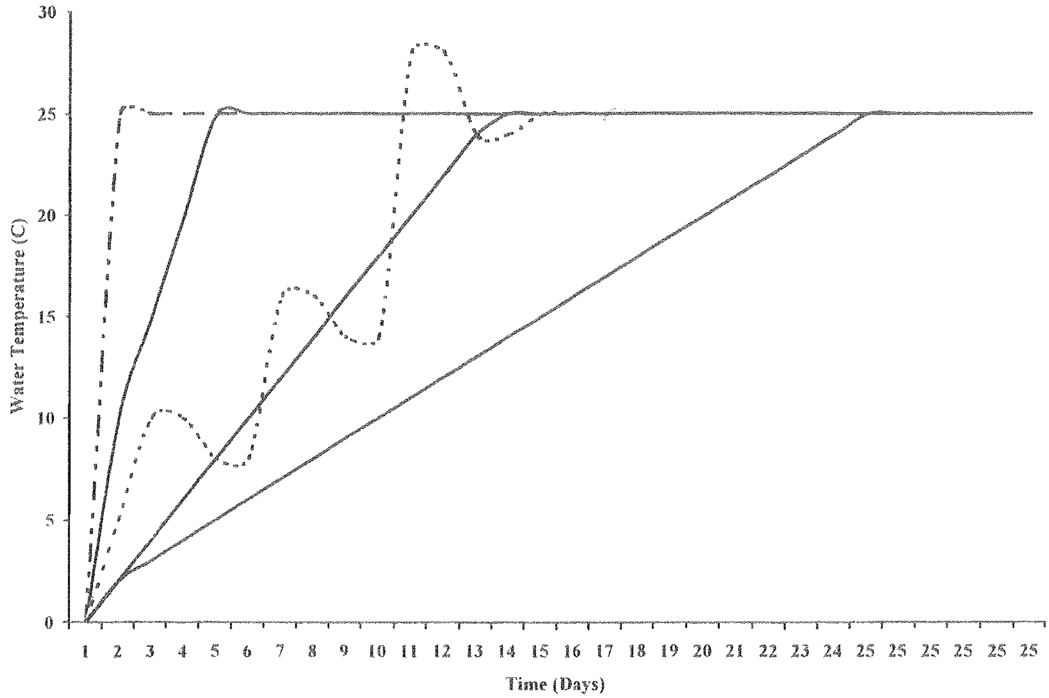

Fig. 7. Simulated temperature variations such as those shown could be produced using the geothermal temperature control system to study biological responses in ponds.

those held at a constant temperature (Davis et al., 1986). Although spawning can occur at static temperatures, channel catfish are adapted to spawn during the spring and thus a more variable temperature profile may be more conducive to spawning. Therefore, future designs for control systems should compare temperature profiles for maximization of egg production within one season. Such designs might include a linear increase in temperature, stepwise increases, emulation of spring cold snaps or controlled magnitude of variations (Fig. 7).

5. Conclusions

The development of a robust process control system for temperature control in channel catfish broodstock ponds focused on the biological constraints. Testing during early spring showed the system capable of maintaining a temperature of 27 ± 2 °C while ambient temperatures varied between 15 and 25 °C. This allowed early production of egg masses. The hardware was built to withstand use on the pond bank, while software and wiring used a combination of commercially available components available at modest cost. Considering the economic incentives, it is expected that this technology may be adapted for use in areas where supplies of warm water, whether geothermal, solar-heated or a byproduct of industrial processes, are available. In addition, the system was flexible in allowing easy programming to yield different conditions, including cyclic heating and cooling to mimic diurnal cycles, or pond cooling if required.

This design was effective in providing control over water temperatures and extending the period of egg production. Affordability should improve as electronics costs continue to drop. More complex simulations of spring heating and cooling events (e.g. diurnal variations and seasonal amplitude variations) may allow a more complete understanding of the relationship between temperature variations and biological responses. In addition, cooling methodologies can be explored with this system, including maintenance of reproduction during the summer.

In addition to the advancement of spawning by the supplemental heating of ponds, temperature manipulation can be used to delay spawning and thus presumably prevent gonadal regression. Spawning of channel catfish was delayed until November in fish held in earthen ponds at ~ 18 °C for 109 days (Brauhn, 1971). To ensure a supply of ripe fish after the normal spawning season, process control could be used to maintain broodstock in reproductive condition by holding pond temperatures within the range of 24–30 °C, using cool water instead of warm (< 23 °C) until the desired time of spawning. It is accepted that channel catfish must undergo some period of gonadal regression and recrudescence, because it is during this period that ovarian yolk deposition occurs (MacKenzie et al., 1989). Furthermore, it is believed that a decline in serum estrogen levels occurs prior to spawning, and this decline is linked with the peaking of the GSI in May (Lambda et al., 1983; Davis et al., 1986). The required duration of time for regression and recrudescence in channel catfish is unknown, although channel catfish have been able to spawn at 6-month intervals when subjected to manipulation of photoperiod and temperature in indoor recirculating systems (Kelly and Kohler, 1996). The present study proved that temperature control is possible in ponds and useful for extending the spawning season.

Process control is a useful tool in the culture and study of fishes that have specific temperature requirements. For example, tilapia (genus *Oreochromis*) are popular high-value culture species, but cannot be cultured in many areas because of their intolerance of cold (~ 15 °C and below). Given a reliable heating source, process control could be used to maintain tilapia in outdoor systems with minimal labor requirements. The Malaysian prawn *Macrobrachium rosenbergii* is similar in that temperature requirements hinder otherwise profitable operations. Process control has been used to maintain temperatures in prawn culture ponds within the range of 25–29 °C by use of thermostats and solenoid valves (Johnson and Smith, 1981) to rear prawns in Oregon, where temperatures are routinely too low for the survival and growth of the species.

Other applications of process control heating of ponds may focus on using this or a related system to study cold tolerance of species such as Nile tilapia *Oreochromis nilotica*. Improvements in programming algorithms and long-term testing are needed to develop the system, and similar low-cost, robust control systems designed with biology in mind may contribute to future scientific and commercial work. Once protocols are developed for particular combinations of species and climate, the CR23X controller could be replaced by less expensive control modules. Further consideration of biology and the physical environment will be needed for future development. For example, feedforward mechanisms (e.g. intelligent algorithms that use predicted temperature profiles) may be considered for cold fronts or warm fronts to avoid excess cooling or heating. Variable flow possibilities are also available. By timing the period when an "open" signal was sent, software could provide a partially open valve that would allow more exact control of temperature. Control of temperature change rates and time–temperature profiles should also be considered. Further studies will address development of this and other systems to improve control. Additional control algorithms and further testing of this and related systems could improve study and culture of aquatic species in engineered systems.

Acknowledgements

This work was supported in part by funding from the US Department of Agriculture, the Louisiana Sea Grant College Program and the Louisiana Catfish Promotion and Research Board. The authors thank R. Price, C. Drapcho and R. Edling of the LSU Department of Biological and Agricultural Engineering for review of the manuscript. The authors also wish to thank R. Romaire, K. Riley, E. Herbst, C. Lambert, B. Whaley, P. Pawiroredjo, G. Polco, J. Stander and A. Nickens of the LSU Agricultural Center Aquaculture Research Station and J. Hargreaves of Mississippi State University for their assistance during this project. This publication has been approved by the director of the Louisiana Agricultural Experiment Station as manuscript number 02-22-0446.

References

Brauhn, J.L., 1971. Fall spawning of channel catfish. Progressive Fish Culturist 33, 150–152.

Brauhn, J., McCraren, J., 1975. Ovary maturation in channel catfish. Progressive Fish Culturist 37, 209–212.

Busch, R.L., 1985. Channel catfish culture in ponds. In: Tucker, C.S. (Ed.), Channel Catfish Culture. Elsevier, Amsterdam, pp. 13–84.

Clapp, A., 1929. Some experiments in rearing channel catfish. Transactions of the American Fisheries Society 59, 114–117.

Davis, K.B., Goudie, C.A., Simco, B.A., MacGregor, R., III, Parker, N.C., 1986. Environmental regulation and influence of the eyes and pineal gland on the gonadal cycle and spawning in channel catfish *Ictalurus punctatus*. Physiological Zoology 59, 717–724.

Huner, J.V., Dupree, H.K., 1984. Methods and economics of channel catfish production, and techniques for the culture of flathead catfish and other catfishes. In: Dupree, H.K., Huner, J.V. (Eds.), Third Report to the Fish Farmers. US Fish and Wildlife Service, Washington, DC, pp. 44–82.

Kelly, A., Kohler, C., 1996. Manipulation of spawning cycles of channel catfish in indoor water-recirculating systems. Progressive Fish Culturist 58, 221–228.

Johnson, W., Smith, K., 1981. Use of geothermal energy for aquaculture purposes, phase III, No. 10990128, Final Report, Geo-Heat Center, Oregon Institute of Technology, Klamath Falls, OR.

Lambda, V.J., Goswami, S.V., Sundaraj, B.J. 1983. Circannual and circadian variation in plasma levels of steroids (cortisol, estradiol, and testosterone) correlated with the annual gonadal cycle of the catfish, *Heteropneustes fossilis* (Bloch). General Comparative Endocrinology 50, 206–226

Lang, R.P., 2001. Induction of early out-of-season spawning in channel catfish *Ictalurus punctatus*. Master's thesis, Louisiana State University, Baton Rouge, Louisiana, 153 pp.

Lund, J.W., Boyd, T.L., 2000. Geothermal direct-use in the United States in 2000. Geo-Heat Center Quarterly Bulletin 21, 1–5.

MacKenzie, D.S., Thomas, P., Farrar, S.M., 1989. Seasonal changes in thyroid and reproductive steroids in female channel catfish *Ictalurus punctatus* in pond culture. Aquaculture 78, 63–80.

Steeby, J.A., 1987. Effects of container type and placement depth on channel catfish spawning success in ponds. The Progressive Fish Culturist 49, 308–310.

Tucker, C., Robinson, E., 1990. Channel Catfish Spawning Handbook. AVI Books, New York, New York.

USDA, 2000. Aquaculture Outlook. National Agriculture Statistics Service. October 10 report, 18 pages