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# Methods for Estimating Water Withdrawals for Aquaculture in the United States, 2005

Scientific Investigations Report 2009–5042

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**U.S. Department of the Interior**
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**U.S. Geological Survey**
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# Converion Factors

| Multiply | By | To obtain |
|---|---|---|
| inch (in.) | 25.4 | millimeter (mm) |
| foot (ft) | 0.3048 | meter (m) |
| acre | 43,560 | square foot ($ft^2$) |
| acre | 4,047 | square meter ($m^2$) |
| acre | 0.001562 | square mile ($mi^2$) |
| pound (lbs) | 0.4536 | kilogram (kg) |
| gallon (gal) | 3. 785 | liter (L) |
| gallon per minute (gal/min) | 0.06309 | liter per second (L/s) |
| gallon per day (gal/d) | 3.785 | liter per day |
| million gallons per day (Mgal/d) | 1.121 | thousand acre-feet per year |
| million gallons per day (Mgal/d) | 0.001547 | thousand cubic feet per second |
| million gallons per day (Mgal/d) | 0.6944 | thousand gallons per minute |
| million gallons per day (Mgal/d) | 0.003785 | million cubic meters per day |
| million gallons per day (Mgal/d) | 1.3815 | million cubic meters per year |
| acre-foot per year (acre-ft/yr) | 1,233 | cubic meter per year ($m^3$/yr) |
| acre-foot per year (acre-ft/yr) | 0.001233 | cubic hectometer per year ($hm^3$/yr) |

# Methods for Estimating Water Withdrawals for Aquaculture in the United States, 2005

By John K. Lovelace


## Abstract

Aquaculture water use is associated with raising organisms that live in water—such as finfish and shellfish—for food, restoration, conservation, or sport. Aquaculture production occurs under controlled feeding, sanitation, and harvesting procedures primarily in ponds, flow-through raceways, and, to a lesser extent, cages, net pens, and tanks. Aquaculture ponds, raceways, and tanks usually require the withdrawal or diversion of water from a ground or surface source. Most water withdrawn or diverted for aquaculture production is used to maintain pond levels and/or water quality. Water typically is added for maintenance of levels, oxygenation, temperature control, and flushing of wastes.

This report documents methods used to estimate withdrawals of fresh ground water and surface water for aquaculture in 2005 for each county and county-equivalent in the United States, Puerto Rico, and the U.S. Virgin Islands by using aquaculture statistics and estimated water-use coefficients and water-replacement rates. County-level data for commercial and noncommercial operations compiled for the 2005 Census of Aquaculture were obtained from the National Agricultural Statistics Service. Withdrawals of water used at commercial and noncommercial operations for aquaculture ponds, raceways, tanks, egg incubators, and pens and cages for alligators were estimated and totaled by ground-water or surface-water source for each county and county equivalent.

Use of the methods described in this report, when measured or reported data are unavailable, could result in more consistent water-withdrawal estimates for aquaculture that can be used by water managers and planners to determine water needs and trends across the United States. The results of this study were distributed to U.S. Geological Survey water-use personnel in each State during 2007. Water-use personnel are required to submit estimated withdrawals for all categories of use in their State to the U.S. Geological Survey National Water-Use Information Program for inclusion in a national report describing water use in the United States during 2005. Water-use personnel had the option of submitting the estimates determined by using the methods described in this report, a modified version of these estimates, their own set of estimates, or reported data for the aquaculture category. Estimated withdrawals resulting from the method described in this report are not presented herein to avoid potential inconsistencies with estimated withdrawals for aquaculture that will be presented in the national report, as different methods used by water-use personnel may result in different withdrawal estimates. Estimated withdrawals also are not presented to avoid potential disclosure of confidential information for individual aquaculture operations.


## Introduction

Aquaculture water use is associated with raising organisms that live in water—such as finfish and shellfish—for food, restoration, conservation, or sport. Aquaculture production occurs under controlled feeding, sanitation, and harvesting procedures primarily in ponds, flow-through raceways, and, to a lesser extent, cages, net pens, and tanks (Hutson and others, 2004). Aquaculture ponds, raceways, and tanks usually require the withdrawal or diversion of water from a ground or surface source. Cages and pens for finfish and shellfish generally are placed in a water body, such as a lake, stream, or ocean that does not require withdrawal or diversion of water; however, cages and pens for alligators generally require withdrawals of water. Most water withdrawn for aquaculture production is used to maintain pond levels and/or water quality. Water typically is added for maintenance of levels, oxygenation, temperature control, and flushing of wastes.

Aquaculture operations using freshwater ponds, raceways, and tanks in the United States typically raise catfish, trout, bass, perch, tilapia, bait fish, sport fish, ornamental fish, crayfish, shrimp, alligators, and turtles. Of the 4,300 aquaculture operations in the United States in 2005, the percentage of operations using each method was as follows: ponds, 54 percent; raceways, 10 percent; tanks, 17 percent; and other methods, 19 percent. The number of aquaculture operations included the following: catfish, 1,160; crayfish, 650; trout 410; ornamental fish, 360; and baitfish, 260 (National Agricultural Statistics Service, 2006).

Estimates of water withdrawn for aquaculture have been included in U.S. Geological Survey (USGS) reports describing water withdrawals for all categories of use in the United States since 1960. However, from 1960 to 1995, water withdrawn for fish hatcheries, fish farms, and other aquaculture was included in other water-use categories including commercial (Solley and others, 1993; Solley and others, 1998), self-supplied industrial (MacKichan and Kammerer, 1961; Murray, 1968; Murray and Reeves, 1972; Murray and Reeves, 1977), rural (Solley and others, 1983), livestock (Solley and others, 1983; Solley and others, 1988), and animal specialties (Solley and others, 1993; Solley and others, 1998). In 2000, water used for aquaculture was presented as an independent category (Hutson and others, 2004). Aquaculture withdrawals typically are less than one percent of total national water use (Hutson and others, 2004, p. 26) and are relatively minor in most States when compared to withdrawals for other categories of use, such as public supply, irrigation, self-supplied industrial, and power generation. Estimated withdrawals for aquaculture also are often published in reports of water-use estimates for individual States.

Estimates of water withdrawals for various categories of use are needed for water planning and management. Water-use data also are needed to evaluate the effects of human activity on the quantity and quality of the Nation's water resources. Aquaculture operations in some States may be required to maintain water-use records and report this usage to a regulatory agency; however, much of the water used for aquaculture in the United States is not reported. Where water withdrawals for aquaculture are unknown, they usually have been estimated by using aquaculture statistics, such as pond acreage, and a water-use coefficient or water-replacement rate (Solley and others, 1998, p. 36). Aquaculture statistics are available from sources such as State agricultural agencies, the U.S. Department of Agriculture Cooperative Extension Service, or the U.S. Department of Agriculture National Agricultural Statistics Service (NASS). Withdrawal coefficients for aquaculture often are available from Cooperative Extension Service agents, local experts, and various aquaculture management publications. Coefficients often vary from State to State depending on livestock management practices, water availability, climatic conditions, and local knowledge of how these factors affect water needs. Use of a consistent method for estimation of withdrawals could help improve the accuracy and consistency of results.

## Purpose and Scope

This report documents methods used to estimate withdrawals of fresh ground water and surface water for aquaculture in 2005 for each county and county-equivalent in the United States, Puerto Rico, and the U.S. Virgin Islands by using aquaculture statistics and estimated water-use coefficients and water-replacement rates. Withdrawals of water used at commercial and noncommercial operations[1] for aquaculture ponds, raceways, tanks, egg incubators, and pens and cages for alligators were estimated and totaled by ground-water or surface-water source for each county and county equivalent. Off-farm water[2] and saltwater[3] used for aquaculture were not included in this study. Use of the methods described in this report, when measured or reported data are unavailable, could result in more consistent water-withdrawal estimates for aquaculture that can be used by water managers and planners to determine water needs and trends across the United States.

Estimates of water withdrawals for aquaculture during 2005 in each county and county-equivalent in the United States, Puerto Rico, and the U.S. Virgin Islands were prepared by using the methods described herein as an alternative to USGS water-use personnel in each State preparing estimates for their State. The estimates were distributed to USGS water-use personnel in each State during 2007. Water-use program personnel are required to submit estimated withdrawals for all categories of use in their State to the USGS National Water-Use Information Program for inclusion in a national report describing water use in the United States during 2005. Water-use program personnel had the option of submitting the water-use estimates determined using the methods described in this report, a modified version of these estimates, their own set of estimates, or reported data for the aquaculture category. Estimated withdrawals resulting from the method described in this report are not presented herein to avoid potential inconsistencies with estimated withdrawals for aquaculture that will be presented in the national report, as different methods used by water-use personnel may result in different withdrawal estimates. Estimated withdrawals also are not presented to avoid potential disclosure of confidential information for individual aquaculture operations. Some water-use coefficients used to estimate withdrawals, such as water-replacement rates for ponds and tanks, also are not presented for this reason.

## Acknowledgments

The author gratefully acknowledges the assistance and cooperation of U.S. Geological Survey hydrologists in each State who provided aquaculture coefficients and other pertinent water-use data for their State. Thanks also to William Alley, Susan Hutson, Kristin Linsey, Joan Kenny, Molly Maupin, and Nancy Barber of the USGS for their guidance and input. Special thanks are given to Brad Summa, Robert Hood, Nathan Crisp, and Matt Guilbeau of the National Agricultural Statistics Service for providing access to and assistance with aquaculture data and statistics.

[1] Commercial aquaculture operations produce and sell aquaculture products. Noncommercial aquaculture operations produce and distribute, rather than sell, aquaculture products (National Agricultural Statistics Service, 2006). Noncommercial operations are often owned and operated by State or Federal government agencies.

[2] Off-farm water is water supplied to an aquaculture operation by a public or private water supplier (National Agricultural Statistics Service, 2006). Withdrawals for off-farm water would be reported under another water-use category, such as public supply.

[3] Saltwater is water from a sea or ocean (National Agricultural Statistics Service, 2006).

# Water Requirements for Aquaculture in the United States

The amounts of water required for aquaculture vary depending on the methods used. Common methods used for culturing freshwater aquatic animals in the United States include ponds, raceways, tanks, pens, and cages (Buttner and others, 1992; Beem, 1998). Many aquacultured species are raised from eggs in commercial or noncommercial hatcheries.

## Ponds

Ponds are used to culture catfish, bass, yellow perch, tilapia, and a variety of other bait, ornamental, or sport fish (Rakocy and McGinty, 1989; Morris, 1993; Riepe, 1997; Morris and others, 1999; Auburn University and Natural Resources Conservation Service, 2004a). More than 60 percent of the 280,000 acres of aquaculture ponds in the United States in 2005 were used to raise catfish. Ponds also are used to raise crayfish, shrimp, prawns, alligators, and turtles (Masser, 1993a; Lutz, 2000; Auburn University and Natural Resources Conservation Service, 2004b; Auburn University and Natural Resources Conservation Service, 2004c). Many crayfish are cultured in shallow ponds, often on cropland also used to grow rice. In 2005, 77,000 acres of cropland ponds were used to raise crayfish (National Agricultural Statistics Service, 2006).

Ponds used for aquaculture vary in size and depth and depend on various factors including species and type of pond. Levee ponds are created by excavating the pond area to a shallow depth and by using the excavated soil to build a perimeter of levees or dikes. Watershed ponds are created by damming ravines or small valleys (Beem, 1998). Recommended pond depths for most fish range from 2 to 8 ft (Rakocy and McGinty, 1989; Welborn and Brunson, 1997; Knud-Hansen, 1998; Natural Resources Conservation Service, 2004). Recommended pond depths for crayfish range from 1 to 2 ft (Lutz and others, 2003; Auburn University and Natural Resources Conservation Service, 2004b).

The amount of water added to aquaculture ponds during the year is highly variable and dependent on several factors including precipitation, evaporation, leakage rates, species needs, and pond management techniques. Some ponds are drained at least once during the year for harvest or water change; some ponds are drained about once every 6 years to renovate fish stocks; whereas others are only drained every 15 to 20 years for repairs and earthwork (Auburn University and Natural Resources Conservation Service, 2002). Some ponds are continuously or regularly flushed (partially drained and refilled) to improve water quality, primarily by adding oxygen and removing wastes. In most ponds used to raise fish, water is added throughout the year to maintain water levels and improve water quality. Rates of water replacement generally range from 0.7 to 9 ft per year (Welborn, 1987; Kidd and Lambeth, 1995; Auburn University and Natural Resources Conservation Service, 2002; Lutz and others, 2003). Water-replacement rates previously used by USGS hydrologists to estimate water withdrawals for aquaculture ponds, primarily catfish ponds, range from 2.7 to 4.5 ft/yr (Holland, 1992; D.E. Burt, U.S. Geological Survey, written commun., 2000; W.S. Mooty, U.S. Geological Survey, written commun., 2005; B.P. Sargent, U.S. Geological Survey, oral commun., 2005). Crayfish ponds generally are filled in early fall and drained in the late spring, then left dry until the following fall (Auburn University and Natural Resources Conservation Service, 2004b). Water-replacement rates for crayfish ponds previously used by USGS hydrologists (B.P. Sargent, U.S. Geological Survey, oral commun., 2006) and suggested for best management practices (Auburn University and Natural Resources Conservation Service, 2004b) range from 1.75 to 2.36 ft/yr.

Stocking rates for pond-raised catfish generally range from 3,250 to 7,000 lbs/ac (Welborn, 1987; Beem, 1998; Morris, 1993; Posadas, 2000; Lutz and others, 2003; Auburn University and Natural Resources Conservation Service, 2004a; Brune and others, 2004). Stocking rates for other pond fish generally range from 1,100 to 11,400 lbs/ac (Rakocy and McGinty, 1989; Riepe, 1997; Kentucky State University, 1998; Morris and others, 1999; Auburn University and Natural Resources Conservation Service, 2004a; Engle and Neira, 2005). Stocking rates for adult turtles generally range from 7,500 to 15,000 turtles per acre (Lutz, 2000).

## Raceways

Raceways are used to culture a variety of fish, including trout, salmon, bass, and catfish, but the most common is rainbow trout (Hinshaw and others, 2004). Raceways are earthen or concrete linear channels into which water is diverted as a continuous stream from an adjacent spring or stream. Raceway dimensions typically range from 50 to 100 ft long, 10 to 30 ft wide, and 3 to 6 ft deep. Raceways are often constructed in pairs and in series so that water will flow from one tank to the next by gravity. Raceways are typically single-pass or flow-through systems. Water is rarely recirculated, but is reused serially with aeration or oxygenation between tanks (Kentucky Aquaculture Task Force, 1998; Natural Resources Conservation Service, 2001; Auburn University and Natural Resources Conservation Service, 2004d).

Constant water movement is needed to maintain dissolved-oxygen concentrations, control temperature, and remove wastes. Rates of water flow through raceways are highly variable and dependent on the water source, species needs, and stocking rates, but they typically are adequate to provide three or more water exchanges per hour with a minimum velocity of about 0.1 ft/sec or 500 gal/min (Cain and Garling, 1993; Shelton, 1993; Beem, 1998; Auburn University and Natural Resources Conservation Service, 2004d; Hinshaw and others, 2004). In 2005, there were about 9,200 raceways with an average flow rate of 632 gal/min in the United States (National Agricultural Statistics Service, 2006).

Stocking rates in raceways are dependant on flow rates and fish species and size. Stocking rates for salmon and trout typically range from 2.5 to 100 lbs/(gal/min of flow) (Rakocy, 1989; Kentucky Aquaculture Task Force, 1998; Dunning and Sloan, 2001; San and others, 2001; Wynne, 2003; Hinshaw and others, 2004).

## Recirculating and Nonrecirculating Tank Systems

Aquaculture tanks often are used to culture trout, salmon, hybrid striped bass, tilapia, yellow perch, sturgeon, walleye, and red drum. Tanks, like raceways, may be arranged in parallel or series. Tanks are often circular or elongated with water velocities sufficient (6 to 12 in/s) to move settleable solids to center drains. Circular tanks used for trout and salmon typically range from 40 to 140 ft in diameter, with diameter-to-depth ratios ranging from 3:1 to 10:1 (Stickney, 2000).

Tanks may be on recirculating or nonrecirculating systems. In recirculating tank systems, water quality is maintained by pumping tank water through special filtration and aeration or oxygenation equipment. Between 85 and 97 percent of the water is recycled and water-replacement rates range from 0.03 to 0.15 percent of the tank volume per day (Rakocy and others, 1989; Valenti, 1997; Masser and others, 1999; Asano and others, 2000; Coffey and Bowser, 2002). Some water is removed from the system during waste removal and cleaning, and water also is lost to evaporation. Nonrecirculating tank systems, like raceways, are single-pass systems that discharge water after its use and require a steady supply of new water. Water-replacement rates for nonrecirculating tank systems range from 16 to 108 percent of the tank volume per day (Allen, 1974; Losordo and others, 1998; San and others, 2001).

## Pens and Cages

Pens and cages used for finfish and shellfish typically are wire or net enclosures placed in a water body, such as an ocean, bay, inlet, lake, or stream. Because no water is withdrawn or diverted for these types of pens and cages, they are considered to be supplied by in-stream flow and were not included in this study.

However, alligators generally are raised in indoor concrete pens or cages, which include land and water areas. The water area typically is a shallow pool at one end of the enclosure. Recommended pen and pool sizes vary depending on the length of the alligators. Pool depths typically range from 10 to 12 inches for grown-out facilities, where young alligators are grown to marketable size, but depths of 6 ft or greater are recommended for breeding. Water is used for waste removal, sanitation, and water exchanges in the pools (Masser, 1993a; Masser, 1993b). Water requirements for alligators generally range from 2 to 3 gal/d per alligator (L. de la Bretonne, Louisiana Cooperative Extension Service, oral commun., 1990; L. McNease, Louisiana Department of Wildlife and Fisheries, oral commun., 1990). Estimated water withdrawals for pens and cages used for alligators are included in the total withdrawal estimates in this study.

## Egg Incubators

Most fish hatcheries incubate eggs in incubators consisting of horizontal trays, vertical trays, or upwell jars (Hinshaw, 1990). Each incubator unit holds between 4 and 16 trays or jars. The number of eggs in each incubation unit depends on the number of trays or jars and the species of fish but generally ranges from about 30,000 eggs in a small (4-tray) unit to 192,000 eggs in a large (16-tray) unit. Water flows over the eggs at rates that generally range from about 1 to 2 gal/min for walleye and yellow perch and about 4 to 7 gal/min for trout and salmon (Hinshaw, 1990; Wynne, 1997). After hatching, the small fish are placed in start tanks or troughs, then later moved to ponds, raceways, or tanks. The majority of fish egg production in the United States is for striped bass, salmon, trout, and walleye (National Agricultural Statistics Service, 2006).

# Methods for Estimating Water Withdrawals for Aquaculture

Ground-water, surface-water, and total withdrawals by commercial and noncommercial operations in each county were estimated by using county-level data for commercial and noncommercial aquaculture operations provided by NASS and water-use coefficients. County-level data for commercial and noncommercial operations compiled for the 2005 Census of Aquaculture were obtained from the NASS (Brad Summa, National Agricultural Statistics Service, written commun., 2007). The data included information that was not released in National Agricultural Statistics Service (2006) to avoid disclosure of confidential information for individual operations.

Total withdrawals were estimated for commercial and noncommercial aquaculture operations and subdivided into withdrawals from ground-water and surface-water sources. All withdrawals were considered self-supplied. Only freshwater withdrawals were compiled as part of the total. Data obtained from NASS for commercial and noncommercial operations were compiled and presented differently and required different estimation methods. Estimated withdrawals from ground-water and surface-water sources for commercial and noncommercial operations in each county were combined to produce county totals. The following equation was used:

$$Wt = Wcgw + Wcsw + Wncgw + Wncsw \quad (1)$$

where

$Wt$ = total water withdrawals, in million gallons per day;

$Wcgw$ = total ground-water withdrawals for commercial operations, in million gallons per day;
$Wcsw$ = total surface-water withdrawals for commercial operations, in million gallons per day;
$Wncgw$ = total ground-water withdrawals for noncommercial operations, in million gallons per day; and
$Wncsw$ = total surface-water withdrawals for noncommercial operations, in million gallons per day.

Other methods, discussed later in this report, were used to estimate water withdrawals for aquaculture in Puerto Rico and the U.S. Virgin Islands because these areas were not included in the 2005 Census of Aquaculture (National Agricultural Statistics Service, 2006).

## Commercial Operations

Commercial aquaculture operations produce and sell aquaculture products. To qualify for the NASS survey, an operation had to have sales greater than or equal to $1,000 during 2005 (National Agricultural Statistics Service, 2006, p. vi). Data obtained from NASS for each county included the number of farms using ground water, surface water, off-farm water, and saltwater; pond acreage; cropland acreage used for crayfish production; number of raceways and average raceway flow rate; and the total volumes of recirculating and nonrecirculating tank systems. Volumes of water used for egg incubators at commercial operations were not specified in the data obtained from NASS and were assumed to be included in volumes used for tank systems. Area or volume of pools in alligator pens and cages at commercial operations also was not specified and was assumed to be included in pond acreage or tank systems. Total withdrawals at commercial operations were estimated by combining estimated withdrawals for ponds, cropland used for crayfish, raceways, recirculating tanks, and nonrecirculating tanks. The following equation was used:

$$Wc = Wcp + Wcc + Wcr + Wcrt + Wcnrt \tag{2}$$

where
$Wc$ = withdrawals by commercial operations, in million gallons per day;
$Wcp$ = withdrawals for ponds at commercial operations, in million gallons per day;
$Wcc$ = withdrawals for cropland used for crayfish at commercial operations, in million gallons per day;
$Wcr$ = withdrawals for raceways at commercial operations, in million gallons per day;
$Wcrt$ = withdrawals for recirculating tanks at commercial operations, in million gallons per day; and
$Wcnrt$ = withdrawals for nonrecirculating tanks at commercial operations, in million gallons per day.

### Ponds

Water withdrawals for ponds at commercial operations in each county were calculated by multiplying the total pond acreage in the county by a water-replacement rate. The total pond acreage at commercial operations in each county was provided by NASS. The water-replacement rates used in this study for aquaculture ponds are not presented to avoid potential disclosure of confidential information for individual aquaculture operations. The following equation was used:

$$Wcp = Acp * Rcp * Ca \tag{3}$$

where
$Wcp$ = withdrawals for ponds at commercial operations, in million gallons per day;
$Acp$ = commercial pond acreage;
$Rcp$ = water-replacement rate for ponds, in feet per year; and
$Ca$ = 0.00089 (to convert from acre-feet per year to million gallons per day).

### Cropland Used for Crayfish Production

Water withdrawals for crayfish production in each county were calculated by multiplying the total cropland acreage used for crayfish in each county by a water-replacement rate. The total cropland acreage used for crayfish production at commercial operations in each county was provided by NASS. The water-replacement rates used in this study for crayfish production are not presented to avoid potential disclosure of confidential information for individual aquaculture operations. The following equation was used:

$$Wcc = Acc * Rcc * Ca \tag{4}$$

where
$Wcc$ = withdrawals for cropland used for crayfish production at commercial operations, in million gallons per day;
$Acc$ = cropland used for crayfish production at commercial operations, in acres;
$Rcc$ = water-replacement rate for crawfish ponds, in feet per year; and
$Ca$ = 0.00089 (to convert from acre-feet per year to million gallons per day).

### Raceways

Water withdrawals for raceways at commercial operations were calculated by multiplying the number of raceways by the average raceway flow rate in each county. The numbers of raceways and average raceway flow rates at commercial operations in each county were provided by NASS. Average raceway flow rates ranged from 1 to 7,600 gal/min. The following equation was used:

$$Wcr = Ncr * Rcr * Cr \qquad (5)$$

where
$Wcr$ = withdrawals for raceways at commercial operations, in million gallons per day;
$Ncr$ = number of raceways at commercial operations;
$Rcr$ = average raceway flow rate, in gallons per minute; and
$Cr$ = 0.00144 (to convert from gallons per minute to million gallons per day).

## Recirculating Tank Systems

Water withdrawals for recirculating tank systems at commercial operations in each county were calculated by multiplying the total volume of recirculating tanks in a county by a daily water replacement rate. The water-replacement rates used in this study for recirculating tank systems are not presented to avoid potential disclosure of confidential information for individual aquaculture operations. The following equation was used:

$$Wcrt = Vcrt * Rcrt * Crt \qquad (6)$$

where
$Wcrt$ = withdrawals for recirculating tank systems at commercial operations, in million gallons per day;
$Vcrt$ = volume of recirculating tank systems at commercial operations, in gallons;
$Rcrt$ = water-replacement rate, in percent volume per day; and
$Crt$ = 0.000001 (to convert from gallons per day to million gallons per day).

## Nonrecirculating Tank Systems

Water withdrawals for nonrecirculating tank systems at commercial operations in each county were calculated by multiplying the total volume of nonrecirculating tanks in a county and a daily water replacement rate. The water-replacement rates used in this study for nonrecirculating tank systems are not presented to avoid potential disclosure of confidential information for individual aquaculture operations. The following equation was used:

$$Wcnrt = Vcnrt * Rcnrt * Crt \qquad (7)$$

where
$Wcnrt$ = withdrawals for nonrecirculating tank systems at commercial operations, in million gallons per day;
$Vcnrt$ = volume of nonrecirculating tank systems at commercial operations, in gallons;
$Rcnrt$ = water-replacement rate, in percent volume per day; and
$Crt$ = 0.000001 (to convert from gallons per day to million gallons per day).

## Ground-Water and Surface-Water Withdrawals

Estimates of ground-water and surface-water withdrawals for ponds, cropland used for crayfish, recirculating tank systems, and nonrecirculating tank systems at commercial operations were determined based on the percentage of farms that reported using ground water and surface water in each county. The NASS provided the number of aquaculture operations using each water source in each county. The percentage of operations using ground-water or surface-water sources in each county was determined by dividing the number of operations using each source (ground water or surface water) in a county by the sum of operations using ground water, surface water, off-farm water, or saltwater. This sum was greater than the total number of farms in some counties because some farms use water from multiple sources and are counted for each water source. Withdrawals of ground water in each county were estimated by using the following equation:

$$Wcgw = (Wcp + Wcc + Wcrt + Wcnrt) * (Ngw/(Ngw + Nsw + No + Ns)) \qquad (8)$$

where
$Wcgw$ = ground-water withdrawals by commercial operations, in million gallons per day;
$Wcp$ = withdrawals for commercial ponds, in million gallons per day;
$Wcc$ = withdrawals for cropland used for crayfish, in million gallons per day;
$Wcrt$ = withdrawals for commercial recirculating tanks, in million gallons per day;
$Wcnrt$ = withdrawals for commercial nonrecirculating tanks, in million gallons per day;
$Ngw$ = number of commercial operations using ground water;
$Nsw$ = number of commercial operations using surface water;
$No$ = number of commercial operations using off-farm water; and
Ns = number of commercial operations using saltwater.

All raceways at commercial operations were assumed to be supplied by surface water or saltwater. Estimates of surface-water withdrawals for raceways in each county were determined by dividing the number of operations using surface water by the sum of operation using surface water and saltwater. Withdrawals of surface water in each county were estimated by using the following equation:

$$Wcsw = ((Wcp + Wcc + Wcrt + Wcnrt) * (Nsw/(Ngw + Nsw + No + Ns))) + (Wcr * (Nsw/(Nsw + Ns))) \quad (9)$$

where
- $Wcsw$ = surface-water withdrawals at commercial operations, in million gallons per day;
- $Wcp$ = withdrawals for ponds at commercial operations, in million gallons per day;
- $Wcc$ = withdrawals for cropland used for crayfish at commercial operations, in million gallons per day;
- $Wcr$ = withdrawals for raceways at commercial operations, in million gallons per day;
- $Wcrt$ = withdrawals for recirculating tanks at commercial operations, in million gallons per day;
- $Wcnrt$ = withdrawals for nonrecirculating tanks at commercial operations, in million gallons per day;
- $Nsw$ = number of commercial operations using surface water;
- $Ngw$ = number of commercial operations using ground water;
- $No$ = number of commercial operations using off-farm water; and
- $Ns$ = number of commercial operations using saltwater.

## Noncommercial Operations

Noncommercial operations produced and distributed, rather than sold, aquaculture products during 2005. To qualify for the NASS survey, noncommercial operations had to produce an estimated value of $1,000 or more of aquaculture products which were released or distributed for restoration, conservation, or recreation during 2005 (National Agricultural Statistics Service, 2006, p. vi). Noncommercial operations include Federal, State, and tribal fish hatcheries. Data provided by NASS for each county included the number, live weight, and the number of eggs or seed stock for alligators, largemouth bass, striped bass, catfish, crappie, fathead minnow, muskellunge, northern pike, perch, salmon, shad, sunfish, trout, turtles, and walleye. All fish produced were assumed to be raised in ponds or raceways. All largemouth bass, striped bass, catfish, crappie, fathead minnows, muskellunge, northern pike, perch, shad, sunfish, and walleye were assumed to be pond raised. All salmon and trout were assumed to be raised in raceways. All turtles were assumed to be raised in ponds. All eggs were assumed to be hatched in incubators. Pond acreage, raceway flow rates, and incubator flow rates were not available from NASS and were estimated based on average stocking rates and flow rates previously used by USGS hydrologists or presented in aquaculture literature. Withdrawals from groundwater and surface-water sources for noncommercial operations in each county were estimated by summing estimated water withdrawals for ponds, raceways, egg incubators, and pens or cages for alligators. The following equation was used:

$$Wnc = Wncp + Wncr + Wnce + Wnca \quad (10)$$

where
- $Wnc$ = withdrawals at noncommercial operations, in million gallons per day;
- $Wncp$ = withdrawals for ponds at noncommercial operations, in million gallons per day;
- $Wncr$ = withdrawals for raceways at noncommercial operations, in million gallons per day;
- $Wnce$ = withdrawals for egg production at noncommercial operations, in million gallons per day; and
- $Wnca$ = withdrawals for pens and cages for alligators at noncommercial operations, in million gallons per day.

### Ponds

Total pond acreage used by noncommercial operations in each county was estimated by dividing the weight of pond-raised fish and the number of turtles produced in each county by stocking rates. Stocking rates used in this study were 5,000 lbs/ac for catfish, 3,500 lbs/ac for all other pond-raised fish, and 11,250 turtles/ac for turtles. These rates are about the averages of values published in literature (Welborn, 1978; Rackocy and McGinty, 1989; Morris, 1993; Riepe, 1997; Beem, 1998; Morris and others, 1999; Lutz, 2000; Posadas, 2000; Engle and Stone, 2002; Lutz and others, 2003; Auburn University and Natural Resources Conservation Service, 2004a; Engle and Neira, 2005). The following equation was used:

$$Ancp = (Pc/Sc) + (Pof/Sof) + (Nt/St) \quad (11)$$

where
- $Ancp$ = estimated pond acreage at noncommercial operations;
- $Pc$ = weight of catfish produced at noncommercial operations, in pounds;
- $Sc$ = stocking rate for catfish, in pounds per acre;
- $Pof$ = weight of all other pond-raised fish produced at noncommercial operations, in pounds;
- $Sof$ = stocking rate for all other pond-raised fish, in pounds per acre;
- $Nt$ = number of turtles produced at noncommercial operations; and
- $St$ = stocking rate for turtles, in number of turtles per acre.

Water withdrawals for ponds at noncommercial operations in each county were calculated by multiplying the estimated pond acreage at noncommercial operations by a water-replacement rate. The water-replacement rates used in this study for aquaculture ponds are not presented to avoid potential disclosure of confidential information for individual aquaculture operations. The following equation was used:

$$Wncp = Ancp * Rncp * Ca \quad (12)$$

where

$Wncp$ = withdrawals for ponds at noncommercial operations, in million gallons per day;

$Ancp$ = estimated pond acreage at noncommercial operations;

$Rncp$ = water-replacement rate for ponds in feet per year; and

$Ca$ = 0.00089 (to convert from acre-feet per year to million gallons per day).

## Raceways

Water withdrawals for raceways at noncommercial operations in each county were estimated by dividing the pounds of fish produced in raceways at noncommercial operations in a county by a stocking rate. The stocking rate used in this study for raceways was 37.5 lbs/(gal/min of flow) for all raceway fish and is about the average of values published in literature (Rakocy, 1989; Kentucky Aquaculture Task Force; 1998; Kentucky State University, 1998; Dunning and Sloan, 2001; San and others, 2001; Wynne, 2003; Hinshaw and others, 2004). The following equation was used:

$$Wncr = (Pts / Sncr) * Cr \quad (13)$$

where

$Wncr$ = withdrawals for raceways at noncommercial operations, in million gallons per day;

$Pts$ = weight of fish produced in raceways at noncommercial operations, in pounds;

$Sncr$ = stocking rate for fish produced in raceways, in pounds per gallon per minute of flow; and

$Cr$ = 0.00144 (to convert from gallons per minute to million gallons per day).

## Egg Incubators

Water withdrawals for fish egg incubators at noncommercial operations in each county were estimated by multiplying the estimated number of incubators in each county by a flow rate. The flow rate used in this study for incubators was 4 gal/min, which is about the average of values published in literature (Beers, 1985; Hinshaw, 1990; Tucker, 1991; Shelton, 1993; Wynne, 1997). The following equation was used:

$$Wnce = Ni * Ri * Cr \quad (14)$$

where

$Wnce$ = withdrawals for egg incubators at noncommercial operations, million gallons per day;

$Ni$ = number of egg incubators at noncommercial operations ;

$Ri$ = incubator flow rate, in gallons per minute; and

$Cr$ = 0.00144 (to convert from gallons per minute to million gallons per day).

The total number of fish egg incubators used by noncommercial operations in each county was estimated by dividing the number of eggs produced in the county by a stocking rate. The stocking rate used in this study for incubators was 100,000 eggs per incubator, which is about the average of values published in literature (South Santiam Fish Hatchery, [no date]; Beers, 1985; McDaniel and others, 1994; Wynne, 1997; Socorro, 2004). The following equation was used:

$$Ni = Ne / Se \quad (15)$$

where

$Ni$= number of egg incubators at noncommercial operations;

$Ne$= number of eggs produced at noncommercial operations; and

$Se$= stocking rate for eggs, in eggs per incubator.

## Pens and Cages Used for Alligators

Water withdrawals for pens and cages used for alligators at noncommercial operations in each county were estimated by multiplying the number of alligators produced by a water-use rate. The water-use rate used in this study for alligators was 2.5 gal/d per alligator, which was based on a rate previously used by USGS hydrologists to estimate water withdrawals for alligators (B.P. Sargent, oral commun., 2005). The following equation was used:

$$Wnca = Na * R\text{a} * Crt \quad (16)$$

where

$Wnca$ = withdrawals for alligators at noncommercial operations, million gallons per day;

$Na$ = number of alligators at noncommercial operations;

$Ri$ = water-use rate for alligators, gallons per day per alligator; and

$Crt$ = 0.000001 (to convert from gallons per day to million gallons per day).

## Ground-Water and Surface-Water Withdrawals

No data on the sources of water were available from NASS for noncommercial operations. Because of this lack of data, water sources used for noncommercial operations in a county were assumed to be similar to water sources used by commercial operations in the same county. Total water withdrawals for noncommercial aquaculture operations in each county were divided into withdrawals from ground-water and surface-water sources by using the percentage of estimated withdrawals from ground-water and surface-water sources for commercial operations in the county. If there were no estimated withdrawals for commercial operations in a county for 2005, the percentage of ground-water and surface-water withdrawals for aquaculture or animal specialties previously estimated by the USGS for (in order of preference) 2000, 1995, or 1990 were used. Estimated ground-water and surface-water withdrawals for aquaculture or animal specialties in each county for 2000, 1995, and 1990 were accessed April 19, 2006 at *http://water.usgs.gov/wateruse/*. If no withdrawals for aquaculture or animal specialties were available for a county for 2000, 1995, or 1990, water withdrawals for noncommercial operations were divided based on the percentage of total ground-water and surface-water withdrawals for all categories of use in the county in 2000. The following equations were used:

$$Wncgw = Wnc * (Wgwx/Wtx) \quad (17)$$

$$Wncsw = Wnc * (Wswx/Wtx) \quad (18)$$

where

*Wncgw*= total ground-water withdrawals for noncommercial operations, in million gallons per day;

*Wnc*= withdrawals by noncommercial operations, in million gallons per day;

*Wgwx*= (in order of preference) ground-water withdrawals for commercial aquaculture in 2005, ground-water withdrawals for aquaculture in 2000, ground-water withdrawals for animal specialties in 1995, ground-water withdrawals for animal specialties in 1990, or total ground-water withdrawals for all categories of use in 2000, in million gallons per

*Wtx*= (in order of preference) total withdrawals for commercial aquaculture in 2005, total withdrawals for aquaculture in 2000, total withdrawals for animal specialties in 1995, total withdrawals for animal specialties in 1990, or total withdrawals for all categories of use in 2000, in million gallons per day;

*Wncsw*= total surface-water withdrawals for noncommercial operations, in million gallons per day; and

*Wswx*= (in order of preference) surface-water withdrawals for commercial aquaculture in 2005, surface-water withdrawals for aquaculture in 2000, surface-water withdrawals for animal specialties in 1995, surface-water withdrawals for animal specialties in 1990, or total surface-water withdrawals for all categories of use in 2000, in million gallons per day.

## Puerto Rico and the U.S. Virgin Islands

Puerto Rico and the U.S. Virgin Islands were not included in the 2005 NASS Census of Aquaculture, and limited data on aquaculture in these areas were available from NASS. The 2002 Census of Agriculture in Puerto Rico (National Agricultural Statistics Service, 2004) indicated that there were 50 aquaculture operations in Puerto Rico in 2002. The operations produced fish in 192 cuerdas (1 cuerda equals 0.971212 acres) of ponds. Total water withdrawals for aquaculture in Puerto Rico were determined by multiplying the total pond acreage by a water-replacement rate, then converting the result to million gallons per day. The water-replacement rates used in this study for aquaculture ponds in Puerto Rico are not presented to avoid potential disclosure of data for individual aquaculture operations.

Withdrawals in each municipio (county equivalent) were determined by multiplying the total water withdrawals for aquaculture in Puerto Rico by the percentages of aquaculture farms in each municipio. The following equation was used:

$$\mathrm{Tm} = \mathrm{Tpr} * (\mathrm{Nm}/\mathrm{Npr}) \quad (19)$$

where

*Tm*= total water withdrawals for aquaculture in a municipio, in million gallons per day;

*Tpr*= total water withdrawals for aquaculture in Puerto Rico, in million gallons per day;

*Nm*= number of aquaculture operations in a municipio; and

*Npr*= number of aquaculture operations in Puerto Rico.

The 2002 Census of Agriculture in the U.S. Virgin Islands (National Agricultural Statistics Service, 2005) indicated that there was only one aquaculture operation in the U.S. Virgin Islands, on the island of St. Croix, during 2002. No other information about this operation was available from NASS. However, the operation could have been the University of Virgin Islands Aquaculture Experiment Station at St. Croix, which has four recirculating tank systems used to culture tilapia and hydroponic vegetables. Approximately 20 gallons per day are replaced in each tank system (University of the Virgin Islands Agricultural Experiment Station, 2007).

No data on the sources of water were available from NASS for aquaculture operations in Puerto Rico and the U.S. Virgin Islands. Because of this lack of data, water withdrawals for aquaculture in Puerto Rico and the U.S. Virgin Islands were divided into ground-water and surface-water withdrawals by using the methods described for noncommercial aquaculture operations.

# Summary

Aquaculture water use is associated with raising organisms that live in water—such as finfish and shellfish—for food, restoration, conservation, or sport. Aquaculture production occurs under controlled feeding, sanitation, and harvesting procedures primarily in ponds, flow-through raceways, and, to a lesser extent, cages, net pens, and tanks. Aquaculture

ponds, raceways, and tanks usually require the withdrawal or diversion of water from a ground or surface source. Most water withdrawn or diverted for aquaculture production is used to maintain pond levels and/or water quality. Water typically is added for maintenance of levels, oxygenation, temperature control, and flushing of wastes.

Aquaculture operations using freshwater ponds, raceways, and tanks in the United States typically raise catfish, trout, bass, perch, tilapia, bait fish, sport fish, ornamental fish, crayfish, shrimp, alligators, and turtles. Of the 4,300 aquaculture operations in the United States in 2005, the percentage of operations using each method is as follows: ponds, 54 percent; raceways, 10 percent; tanks, 17 percent; and other methods 19 percent. The number of aquaculture operations included the following: catfish, 1,160; crayfish, 650; trout 410; ornamental fish, 360; and baitfish, 260.

Estimates of water withdrawals for aquaculture are needed for water planning and management; however, much of the water used for aquaculture in the United States is not reported. Where water withdrawals for aquaculture are unknown, they usually have been estimated by using aquaculture statistics, such as pond acreage, and a water-use coefficient or water-replacement rate**.** Use of consistent methods for estimation of withdrawals could help improve the accuracy and consistency of results.

This report documents methods used to estimate withdrawals of fresh ground water and surface water for aquaculture in 2005 for each county and county-equivalent in the United States, Puerto Rico, and the U.S. Virgin Islands by using aquaculture statistics and estimated water-use coefficients and water-replacement rates. County-level data for commercial and noncommercial operations compiled for the 2005 Census of Aquaculture were obtained from the National Agricultural Statistics Service. Withdrawals of water used at commercial and noncommercial operations for aquaculture ponds, raceways, tanks, egg incubators, and pens and cages for alligators were estimated and totaled by groundwater or surface-water source for each county and county equivalent.

The results of this study were distributed to USGS water-use personnel in each State during 2007. Water-use personnel are required to submit estimated withdrawals for all categories of use in their State to the National Water-Use Information Program for inclusion in a national report describing water use in the United States during 2005. Water-use personnel had the option of submitting the water-use estimates determined by using the methods described in this report, a modified version of these estimates, their own set of estimates, or reported data for the aquaculture category. Estimated withdrawals resulting from the method described in this report are not presented herein to avoid potential inconsistencies with estimated withdrawals for aquaculture that will be presented in the national report, as different methods used by water-use personnel may result in different withdrawal estimates. Estimated withdrawals also are not presented to avoid potential disclosure of data for individual aquaculture operations.

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