AQUACULTURE EFFLUENTS AND WASTE BY-PRODUCTS

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Characteristics, Potential Recovery, and Beneficial Reuse

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Executive Summary

Many of the world's natural fisheries have been decimated. To meet future seafood demands, aquaculture must continue to grow. However, aquatic resources are limited, and aquaculture development must address the serious concerns of resource allocation, environmental impact, and sustainability.

Current aquaculture activities in the United States vary by region. Although the North Central Region (NCR) is rich in freshwater resources, traditional aquaculture activities (both public and private) have been principally driven toward satisfying the demands for recreational fishing and tourism. Other regions of the United States have specialized in the production of fish and seafood for human food markets (e.g., catfish in the south and salmonids in Idaho).

In contrast to other regions of the United States with more established aquaculture industries, the NCR is heavily populated. Intensive municipal, industrial, and agricultural uses of the local water supply have led to strong legislative and regulatory measures designed to protect these regional aquatic resources. With a clear understanding of the history of both the positive and negative aspects of regional aquaculture development, this region's aquaculture community must develop in a fashion that contributes meaningfully to national and global demands for fisheries products within the framework of legislative and regulatory controls and environmental impacts.

The intent of this report is to:

- Describe the characteristics of effluents and waste by-products of representative aquaculture rearing systems in the NCR
- Explain the relationship of these wastes to their dietary source and the aquaculture production process
- Compare the waste production and water usage of aquaculture systems in comparison with other agricultural, municipal, and industrial production processes
- Review potential methods for wastewater and solids reduction and recovery for beneficial use
- Recommend proactive measures that aquaculturists can use to promote and ensure the minimization of environmental impact and development of more sustainable aquaculture practices for the NCR

Acknowledgements

Preface

According to the U.S. Strategic Aquaculture Plan (JSA 1994), the development of the U.S. aquaculture industry has great potential for immediate and long-term benefit to the nation. Global demand for seafood is projected to increase 70% in the next 30 years, while harvests from capture fisheries are either declining or approaching their limit. Thus, a dramatic increase in aquaculture is needed to supply future seafood needs.

Presently, more than 60% of the U.S. seafood demand is met by imports, resulting in a fisheries trade deficit of several billion dollars annually. Research and development in support of sustainable aquaculture production will improve the ability of the American aquaculturists to supply this country's consumers and the global marketplace with high-quality, affordable fish and shellfish.

Aquaculture in the North Central Region

The North Central Region (NCR) is home to more than a quarter of the U.S. population, a large fraction of which is concentrated in major metropolitan areas such as Chicago, Detroit, Milwaukee, and Cleveland. This region produces only 1% of the fish products used by consumers and accounts for approximately 3% of the U.S. aquaculture production (U.S. Census Bureau 1999). Aquaculture in the region is characterized by great diversity, with more than 50 different species of aquatic animals cultured by more than 1,000 producers of food fish, baitfish, and fish for stocking into recreational water bodies.

Although national trends suggest a pressing future need for aquaculture development with more rapid growth than other sectors of agriculture, the potential for continued regional development will depend on allocation and efficient use of limited water resources among alternative uses and the relative environmental and societal impact of aquaculture compared with these alternatives. "Sustainability" is a deceptively simple concept defined by reducing inputs and reducing waste outputs of energy and materials to ensure the perpetuation of the ecosystems that support us. Beneficial reuse, efficiency of production, and the reduction of environmental impact are key goals in attempting to achieve sustainability. Opinions concerning the benefits and costs of aquaculture vary with the way different "interest groups" perceive the proper use of natural ecosystems and resources (Boyd 1999).

Currently, aquaculture operations in the NCR are typically smaller artisanal production operations, often allied to outdoor recreational fishing and country-style tourism. Systems capable of addressing projected food production needs will require higher levels of production. Concern over continued aquaculture development in the NCR may originate as much from the pressing need of conventional aquaculture rearing techniques for abundant sources of high-quality water and the limited nature of such sites as it does from concern over potential waste production. The economic value of increasingly limited water resources for public water supply, recreation, and tourism can generate formidable conflict over the development of sites for aquaculture. The potential thermal impact of impounding headwaters of cold-water recreational fisheries and the

potential of high-capacity wells to influence nearby groundwater levels are additional aspects of regional aquaculture water usage that can generate conflict and constrain aquaculture growth.

Controversy over allocation of high-quality water resources for aquaculture and its compatibility with alternative uses is likely to continue. Rearing system water usage is closely related to the concentration of waste released and its potential assimilation in the receiving waters. For continued growth and increased sustainability, new aquaculture facilities need to move toward rearing strategies that improve the efficiency of water usage and that minimize the discharge of waste to public water resources. Portions of the organic waste and nutrients generated during aquaculture production have potential beneficial reuse. Characterization of regional aquaculture production systems, their water usage, waste production, and the potential reuse of the organic matter and nutrient by-products are the foci of this report. While the World Aquaculture Society-U.S. Chapter's most recent review of aquaculture and environmental issues (Tomasso 2002) summarizes these issues from a general U.S. perspective, we have focused where possible on cases and examples specific to the NCR.

The suitability of aquaculture wastes for beneficial use depends on the level of contaminating substances with detrimental properties. Of concern in this regard is the degree of usage of chemical therapeutics, herbicides, and water-quality management substances and their persistence in aquaculture waste. Concerns focused on chemical usage relate to the broader issues of drug resistance development and potential disease transference (Blazer and LaPatra 2002). Lastly, the possible escape (Harrell 2002; Myrick 2002) and spread of exotics or transgenic species are also relevant issues to the development of a socially responsible aquaculture industry. However, in this report we are concerned with the potential reuse of aquaculture by-products and have not addressed these concerns.

Aquaculture Effluents and Wastes in Specific Rearing Systems

In 1998, 362 NCR aquaculturists used a variety of culture methods—65% used ponds, 20% used flow-through raceways and tanks; 13% used recirculating systems, and 2% used cages and net-pens. Except for a slightly higher use of flow-through and recirculating systems, regional aquaculture rearing methods are generally similar to the overall U.S. pattern (Figure 1).

The importance of various species differs from state to state within the region (Figure 2). Cold-water trout production occurs in states with adequate supplies of cold surface water or abundant groundwater. Catfish are most important in the southern portions of the region, including Missouri and Illinois, where the growing season is slightly longer. Other alternative food species sales (including walleye, yellow perch, hybrid striped bass, and tilapia) are becoming significant in a majority of the states in the region.

From 1992 through 1994, the North Central Regional Aquaculture Center (NCRAC) Effluent Work Group conducted an investigation characterizing the effluents of regional aquaculture production systems. Rearing systems were classified as a pond, flow-through, cage-culture, or recirculating. These systems vary in the degree of

Aquaculture Rearing Systems Used in the United States

Ponds 63%
Flow-through 14%
Cages 3%
Net-pens 1%
Recirculating 7%
Prepared Bottoms 7%
Other Methods 5%
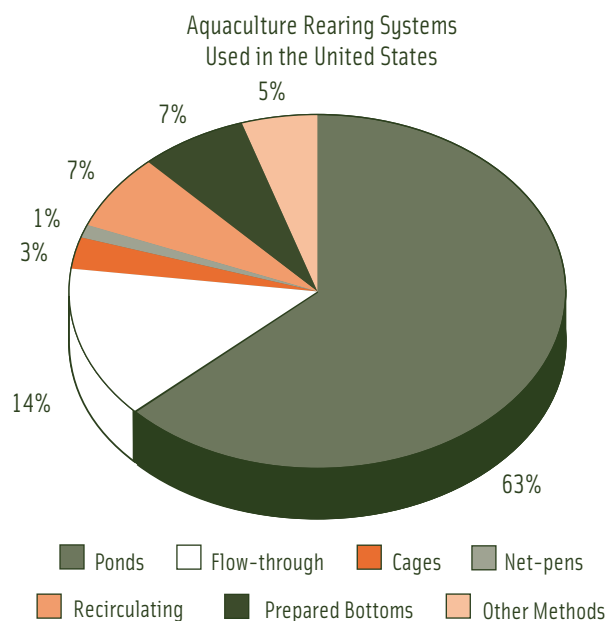
Figure 1. Proportional use of various aquaculture rearing methods for the United States as a whole (USDA 2000).
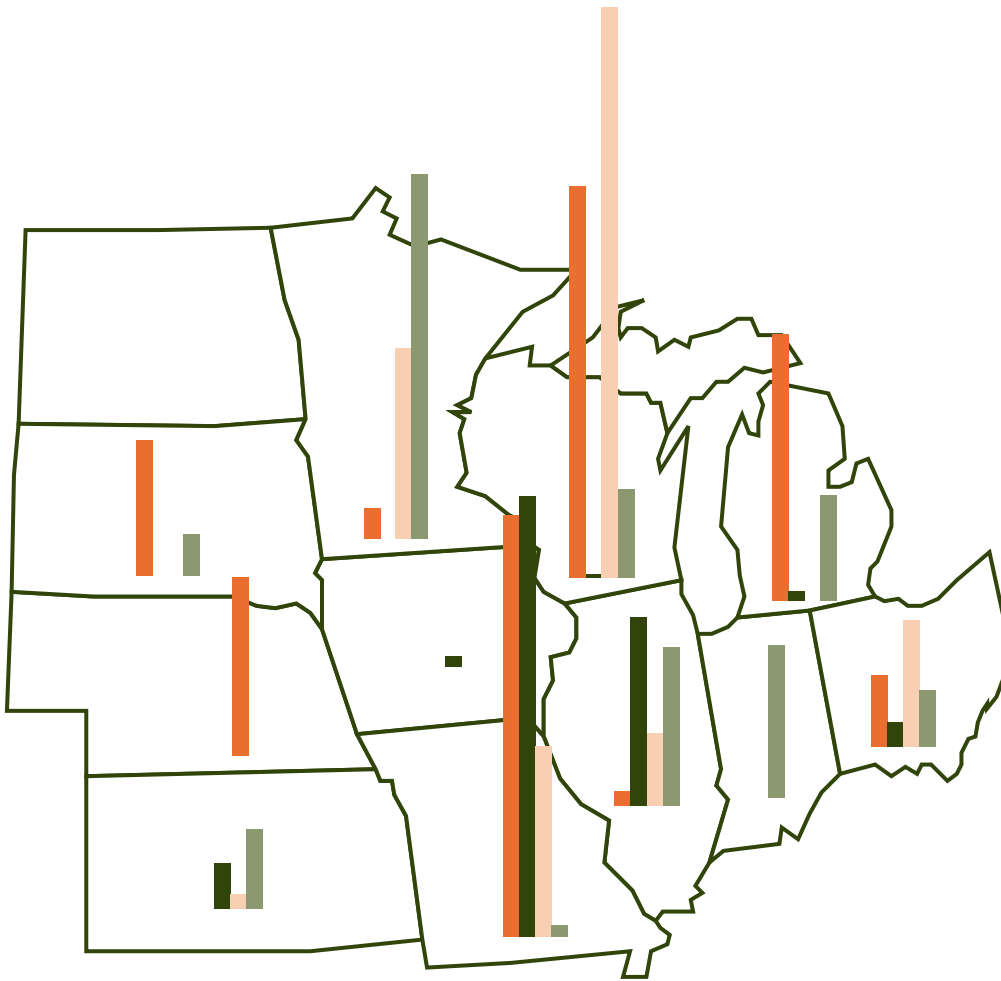
Figure 2. Reported NCR aquaculture sales by state (USDA 2000). Histogram columns from left to right for each state represent ■trout, ■catfish, ■ baitfish, and ■ other food fish, respectively. ("Other food fish" combines walleye, yellow perch, hybrid striped bass, tilapia, etc.). To provide a scale, Wisconsin baitfish sales were $2,455,000 in 1998.

water usage and in the characteristics of the associated "waste" by-products.

Pond Culture

Pond culture is currently the most prevalent rearing method for many species in the NCR. Most commercially produced warm-water species, some cool-water species, and baitfish are typically reared in ponds. In commercial pond culture there is either some degree of fertilization or supplemental feeding to increase production to commercially viable levels, greater than would occur naturally. Ponds differ from flow-through systems in that they are basically static and do not rely on water replacement to maintain water quality. Ponds rely mainly on internal natural processes to purify the water.

The biological community acts upon the dissolved wastes and helps to stabilize and recycle waste. Settled solids accumulate and undergo microbial decomposition in the pond sediment, much in the same way that a municipal water treatment facility functions.

A pond's production capability is directly related to the daily amount of feed that can be added to the pond while still maintaining adequate water quality. In southern catfish ponds, daily feeding rates of 30–50 kg/ha (27–45 lb/acre) limit annual production to 2,000–3,000 kg/ha (1,784–2,676 lb/acre) (Tucker et al. 2001). These low yields are generally considered unprofitable. When feeding rates exceed these, there is increased oxygen demand. As pond production is intensified to 4,000–7,000 kg/ha (3,568–6,244 lb/acre), supplemental aeration must be used to maintain acceptable water quality. Feeding rates of 100–150 kg/ha/day (89–134 lb/acre/day) limit

annual catfish production to 8,000–10,000 kg/ha (7,136–8,921 lb/acre/day) (Cole and Boyd 1986), a level seldom achieved under commercial conditions. Cole and Boyd (1986) pointed out that truly significant improvements in water quality appear possible only by reducing daily feeding rates to values less than about 50 kg/ha/day (45 lb/acre/day).

Pond water quality needs to be well-managed and balanced by aquaculturists for their crops to survive. Even in a nearly static-flow pond, episodic events associated with pond harvest and cleaning or heavy precipitation and flooding can cause the mixing of settled material and its discharge, as concentrated waste, to the surrounding area. Under flood conditions, the additional water can cause pond water to be released and can decrease residence time in the pond, increasing the chance that a portion of the dissolved waste can escape before the pond's natural treatment processes act on it.

The NCRAC Effluent Work Group project characterized the effluents of two Iowa hatcheries: (1) channel catfish ponds at Fairport Hatchery and (2) catfish and hybrid sunfish pond effluents at Kloubec's Fish Farm (NCRAC 1994). Rivera (1995) examined harvest effluents from perch fingerling ponds in Wisconsin. These studies quantified water-quality differences in solids and nutrients during the later stages of harvest and draining events. Rivera (1995) compared older, established fingerling pond effluents with those of newly established ponds and found that settleable solids, biochemical oxygen demand (BOD), and soluble reactive phosphorus were slightly, but significantly, higher in effluents of older ponds, characterized by a higher accumulation of organic matter. Rivera (1995) concluded that the impact of perch-pond effluent on the receiving stream water quality was very localized at the effluent site. She used the Hilsenhoff biotic index (Hilsenhoff 1982) to compare sites above and below the hatchery effluent; this index is based on the relative sensitivity of benthic organisms to stream quality conditions. Rivera (1995) found the overall impact of the hatchery on the biotic community was positive and that the annual drainage events had minimal impact on the local aquatic taxa.

In their recent review, Tucker et al. (2002) (1) encapsulate the results of Southern Regional Aquaculture Center investigations (Tucker 1998) concerned with the characterization and management of effluents from aquaculture ponds in the southeastern United States, (2) review the nature of pond effluents for a variety of important species, (3) provide recommendations for the reduction of environmental impact, and (4) estimate the costs of waste treatments. They also reviewed the potential environmental impact of catfish culture. The trend among catfish farmers has been toward maintaining pond levels to allow for storage of storm water before it

is discharged. This also minimizes discharge of waste and restricts discharges to the episodic storm events that exceed the available storage capacity. Discharges during cleaning and harvest can be addressed by diversion of the flow or other possible technological solutions. The use of constructed wetlands, vegetated infiltration areas, and crop irrigation for recovery or beneficial reuse of pond effluents were examined as part of the Southern Regional Aquaculture Center (SRAC) project (Tucker 1998). Based largely on the long hydraulic residence time of catfish pond rearing as currently practiced, Tucker and Hargreaves (1998) argue that there is little need for further regulation beyond what currently is in place. They also state that current research effort into best management practices (BMPs) will improve the water quality and minimize the quantity of pond discharge.

Tucker (1998) and Tucker et al. (2002) recommendations for reducing the impact of aquaculture ponds are:

- Use high-quality feeds and efficient feeding practices
- Manage within a pond's assimilative capacity
- Provide adequate aeration and circulation of pond water
- Position mechanical aerators to reduce erosion
- Minimize water exchange
- Operate food fish production ponds for several years without draining
- Capture rainfall to reduce pond overflow
- Allow solids to settle before discharging
- Reuse water that is drained from ponds
- Treat effluents by using constructed wetlands
- Use effluents to irrigate terrestrial crops
- Optimize the ratio of watershed to pond area
- Divert excess runoff from large watersheds away from ponds
- Construct ditches to minimize erosion and establish plant cover on banks
- Protect embankments in drainage ditches from erosion
- Maintain plant cover on pond watersheds
- Avoid leaving ponds drained in winter, and close valves once ponds are drained
- Close drain valves when renovating ponds
- Use sediment from within ponds to repair levees, rather than disposing it outside of ponds
- During pond renovation, excavate to increase operational depth (increased water storage will reduce volume of effluent)

Many of these same recommendations are applicable to NCR ponds. Some variations in these management practices are appro-

priate, because there are a much wider variety of species cultured in the NCR. For instance, supplemental well water flow is sometimes used to maintain temperature refuges in production ponds with cool-water fish, e.g., yellow perch. Regional culturists also use shallow natural ponds that winterkill, permitting the culture of small baitfish or fingerlings in the absence of older predatory fish. These ponds are quite different in form and function from southern fish culture ponds.

When ponds are sited in cold headwaters, the possibility of thermal impact on receiving waters with cold-water recreational fisheries can be an issue for the NCR. The concerns are that impoundments reduce available cold-water habitat during the warm seasons and create temperatures colder than groundwater in the winter that might impact salmonid egg incubation.

Flow-Through System

This rearing method is characteristic of cold-water fish hatcheries, as well as for some cool-water species in this region. High rates of water exchange dilute dissolved waste and permit fish to be reared at high densities in raceways, tanks, and ponds. These systems typically operate with very short water retention times, often less than one hour. High fish densities require the feeding of formulated diets. Rearing units of various sizes and shapes are used, including circular units, but the most common is the linear raceway. Concrete and fiberglass are popular construction materials used in public and large commercial hatcheries. Earthen raceways are found among many smaller private facilities. Very often, water flows from pond to pond before being discharged. To achieve greater production potential, pure oxygen injectors, mechanical aeration, or gravity aeration (where topography permits) are employed between rearing units to maintain dissolved oxygen concentrations. Flow-through facilities discharge large quantities of very dilute effluents, making nutrient recovery difficult.

Solid wastes can be settled for collection and periodically removed for disposal or beneficial reuse. Intact feed and fecal waste products readily settle out from the water and can be collected in designated quiescent zones or side-streamed to off-line settling basins. Depending on water flow volume and anticipated total solids load, various technological and design solutions can be applied to collect and recover solids (Westers 1991; IDEQ 1997). Overflow rate of the settling area, water retention time, waste particle settling rates, water velocity flow distribution, and settling area depth are important factors in settling-basin design. For facilities with smaller flow volumes, in-pond or separate basin settling of the full-flow

volume might be considered, but larger-flow facilities are best managed by the removal of collected waste from designed quiescent areas into off-line settling basins. As is seen with pond situations, the disturbance of settled waste during cleaning events may cause episodic increases in the concentrations of waste in the effluent. Researchers in the NCRAC (1994) study of flow-through rearing sites at Sandhills Aquafarms, Nebraska; Rushing Water Hatchery, Wisconsin; and Rathbun Hatchery, Iowa, observed modest but detectable alterations in the level of nitrogenous and phosphorus compounds in the normal hatchery discharges, with more dramatic alteration in water quality during cleaning events.

Guidelines for waste management at flow-through aquaculture facilities have been developed for the Idaho salmonid industry (IDEQ 1997). Development of a waste collection plan for a specific facility depends on its planned production capacity and operational practices.

Waste collection options (IDEQ 1997) for solids removal for aquaculture facilities with small-flow volumes include:

- Settling of solids in the rearing area (in-pond settling)
- Settling and removing solids from a separate basin that receives the full flow from the facility (full-flow settling)
- Collecting the solids in the quiescent areas at the end of the rearing areas and removing this waste to separate off-line basins
- Use of constructed wetlands or alternative treatments

Hinshaw and Fornshell (2002) have recently reviewed studies of the characteristics and management of effluents from raceway culture systems. They found that the enormous variation in reported values illustrates the importance of factors such as mode of operation during measurement, stocking density, composition of feed and feed conversion efficiency, and the intensity of water use. Due to site-specific differences in farms and receiving waters, they found that most generalizations regarding impact of these systems were of limited value. However, they noted two constants: (1) as in other intensive methods of fish culture, the source of nutrient pollution is fish feed, and (2) primary raceway effluents are characterized by high volumes of water with low concentrations of nutrients.

Hinshaw and Fornshell (2002) concluded that of all the potential negative impacts of effluents from raceways, the most common and the most visible still result from the failure to control suspended and settleable solids from leaving the facilities. They further state that of the nearly 700 raceway production systems in the United States, very few have been identified as a cause of severe stream impairment, yet most contribute to some nutrient-related changes in the

stream habitat below their discharges. The degree of impact can be reduced significantly through (1) enhancements in feed quality and feeding efficiency and (2) effective solids capture and handling.

Although dissolved nutrients in effluents can be somewhat reduced by efficient feeding and by rapid removal of solid waste, a large proportion of the excreted waste is in the form of dissolved nitrogen by-products derived from fish metabolism and dissolved phosphorus. Removal of this dissolved material is a more intractable problem than settleable material removal. Even though the concentration of nutrients, especially phosphorus, in the effluent are diluted to low levels, the total load contributed by an intensive rearing operation depends ultimately on the nutrient level in the feed used and how efficiently the feed is actually eaten and assimilated. Close monitoring and efficient control of feeding are paramount to waste reduction. When the flux of nutrients to the receiving waters is increased, nutrient enrichment can occur. This enrichment can accelerate the aging of aquatic systems. This process is termed eutrophication and depends on many factors, including the hydrologic characteristics of the watershed and the overall natural and human activities within the entire watershed. It may be difficult and costly to separate the impact of nutrient load of the fish-rearing operation from the contribution of other nonpoint sources.

While evidence of comparatively slight to moderate nutrient impacts of raceway systems in the United States is confined to a very few specific sites (Hinshaw and Fornshell 2002), ubiquitous agricultural and urban runoff from highly populated and developed areas is increasingly recognized as a major source of nonpoint nutrient loading within the NCR. Nonpoint sources can be more difficult to identify than point source effluents. In addition, the requirement of abundant and high-quality water sources for flow-through rearing results in these systems being sited in areas of high recreational value, cold-water trout streams in particular, further increasing the likelihood of water use conflict. Nationally, the Snake River, Idaho, trout hatcheries and regionally, the Michigan Department of Natural Resources Platte River Hatchery (Whelan 1999) are examples of flow-through rearing operations that have come under scrutiny over the discharge of phosphorus. Strategies to reduce waste through efficient assimilation of the diet and reduction of phosphorus in diet formulations are making progress toward reducing phosphorus release from flow-through facilities.

The large water usage and discharge of flow-through facilities make wetland use for absorption of excess dissolved nutrients by vegetation impractical for the entire hatchery effluent. The areas of wetland required to achieve sufficient residence time (4–10 days) seem too large to be practical for full hatchery flow treatment. If waste can be side-streamed to off-line settling basins with lower flow, constructed wetlands or vegetative buffer areas might be more appropriately employed as an additional treatment for the overflow of the waste removal system. Flow-through rearing systems reusing a significant proportion of their water and employing ammonia removal by dilution and/or other means, such as zeolites (Piper and Smith 1984), may reduce the effluent flow to smaller more concentrated volumes, making these treatment methods practical. Rapid and effective solids removal would be essential. Such a partial recirculation system (between 100% to 10% water replacement/day) would reduce water usage to a level between the current high usage of cold-water production facilities and that of fully recirculating systems (around 10% or less water replaced/day).

Recirculating Aquaculture System (RAS)

While RASs are often much more expensive to build, maintain, and operate than other fish culture methods, fish can be raised under more ideal water conditions throughout the year. RASs occur in a wide variety of configurations, but the essential characteristic of such systems is that they reuse all or a significant portion of their rearing water multiple times. They generally incorporate components that rapidly collect and remove solid waste, aerate or oxygenate the water, and reduce the build-up of toxic metabolites (Chen et al. 2002). In the NCR, RAS units are generally used for production of the newer aquaculture species, e.g., yellow perch, tilapia, and hybrid striped bass. If RASs are coupled with hydroponic plant production (aquaponics), these operations can produce a second profitable crop but are difficult to manage for both optimal plant production and fish waste-product removal.

Chen et al. (2002) describe the major wastewater treatment components and processes in an RAS and the relationship of fish excretion to system design. RASs incorporate their own particulate waste removal apparatus—filtration and/or settling. The heart of an RAS is generally a microbe-based biofilter for conversion of dissolved nitrogenous toxic metabolic waste to relatively nontoxic forms. By their very nature, RASs require large inputs of energy and are more mechanically complex. Effluents from RAS culture can have a high enough nutrient concentration (Red Ewald-style RAS had effluents of >200 mg/L nitrate nitrogen and mean total phosphorus in the 20-30 mg/L range during tilapia production for the NCRAC 1994 study) to support plant or vegetable production (typical hydroponic growth solutions [Resh 1989] have nitrate nitrogen levels of 145 mg/L and 65 mg/L of phosphorus).

In an RAS, settling and filtering devices readily recover larger waste particles, but the turbulence of pumping, typical of these systems, causes disintegration of large particles. The size distribution of solid particles shifts to an abundance of smaller-sized particles, which are difficult to remove (Chen et al. 2002). Due to the concentration of solid waste in limited volumes, wastewater effluents from RASs can feasibly be treated by a constructed wetland system or septic-type disposal system. As with collected solid waste from flow-through systems, recovered solid waste from RASs can also be land applied or further composted and used as a soil conditioner and slow release fertilizer. Further processing, (i.e., dewatering, composting, and bulk storage) may be desirable for effective use of solid waste materials.

Because they reduce water usage and avoid the discharge of large quantities of diluted waste to public receiving waters, these systems are less likely to generate public water resource conflicts. However, the cost of their operation restricts their practical use to highly valued aquaculture products. Also, because the wastewater and sludge produced by RAS systems are concentrated to the point where their BOD is similar to domestic or municipal sewage (Figure 4), the operator still needs an environmentally appropriate means of disposal or reuse of the material.

Cage and Net-Pen

In this type of rearing system, cages or net-pens holding fish at relatively high density are sited in a much larger body of water, and fish are fed a formulated diet. Settled waste passes through the bottom of the pen and is diluted in the surrounding waters. The idea has been proposed that cages or net-pens can be "diapered" to collect and recover waste feed and feces from the bottom of the pen; however, that approach is fraught with technical problems and economically prohibitive (Stickney 2002). Stickney (2002) cites one example (Anonymous 1999) where such a device appears to have been successfully employed. Generally in large net-pens, dissolved waste components are diluted into the surrounding environment, which should be carefully chosen to have good flushing properties. This type of rearing system has aroused a high level of controversy because it relies on the assimilative capacity and dilution of the, often public, host water body for absorbing its wastes. Siting such facilities in areas with high flushing of water and moving the net-pens to permit the areas of settled waste that build up beneath the pens to lie "fallow," are necessary to avoid environmental impact. Fecal material and unused food are potentially highly degrading and difficult to recover in this type of operation.

For the NCR and Great Lakes Basin, net-pen operations have been sited in large bodies of water (Gale 1999) and subjected to close public scrutiny (Dochoda et al. 1999). The eventual demise of Minnesota Aquafarms illustrates this point. Originally conceived as a means of reclaiming abandoned iron-ore mine pits (net-pen production of salmon), this operation became the focus of environmental concern (Hora 1999) related to its possible influence on the regional aquifer that provided drinking water for the local community. Axler et al. (1992a, 1992b, 1993, 1996a, 1996b) have explained this case in detail. Arrangements were made to collect settled waste and pump it to an adjacent pond whose effluent would be further treated for nutrient removal by a constructed wetland (see Axler et al. 1996b). Unfortunately, the company ceased operation before the effectiveness of the wetland could be fully tested.

Effluent Comparisons

Typical ranges of water-quality indicators for representative aquaculture water sources, effluents, and recovered aquaculture sludge versus runoff waters, municipal sewage, and various industrial and agricultural wastes from available literature sources and from recent NCRAC (1994) and SRAC investigations (Tucker 1998) are summarized for comparison in Figures 3-8. Because of the wide range of each of the parameters illustrated, it was necessary to use logarithmic scale on the horizontal axis—meaning that each vertical line represents concentrations 10 times greater than the line to the left of it and 10 times lower than the line to the right of it. Figures 3-12 have horizontal axes, while figure 13 has a vertical axis.

These figures contain representative data from 1994 NCRAC studies of flow-through trout rearing in Nebraska; the cool-water flow-through hatchery in Rathbun, Iowa; tank rearing of yellow perch and whitefish in Wisconsin; summarized data from discharge permit records for Wisconsin Department of Natural Resources Hatcheries; and net increases from Minnesota raceways (Axler et al. 1997). Pond situations include overview data based on SRAC catfish and hybrid striped bass pond data (Tucker 1998); Fairport, Iowa, catfish ponds

(NCRAC 1994); and Wisconsin studies of perch fingerling production ponds (Rivera 1995), including the influence of pond draining. RAS data are based on tilapia production in Illinois (NCRAC 1994) and work on RAS-produced sludge (Ning 1996). Examples of representative runoff from various urban and rural land situations are from storm water and eutrophication studies (NAS 1969; Weibel 1969; Bannerman 1990; Bannerman et al. 1993). Representative examples for various agricultural and manufacturing processes were derived from water and wastewater engineering texts (Fair et al. 1968; McGauhey 1968; Thomann 1983; Haug 1993), and previous reviews comparing aquaculture impacts (Brune and Tomasso 1991; Beveridge et al. 1991; Phillips et al. 1991).

Total Suspended Solids (TSS)

TSS is the weight of filterable solid material suspended in the water column (Figure 3). It differs from settleable solids (SS), which is a measure of the volume or weight of material that will settle from the water column in an hour. SS is a useful measurement for sampling

TSS (mg/L)
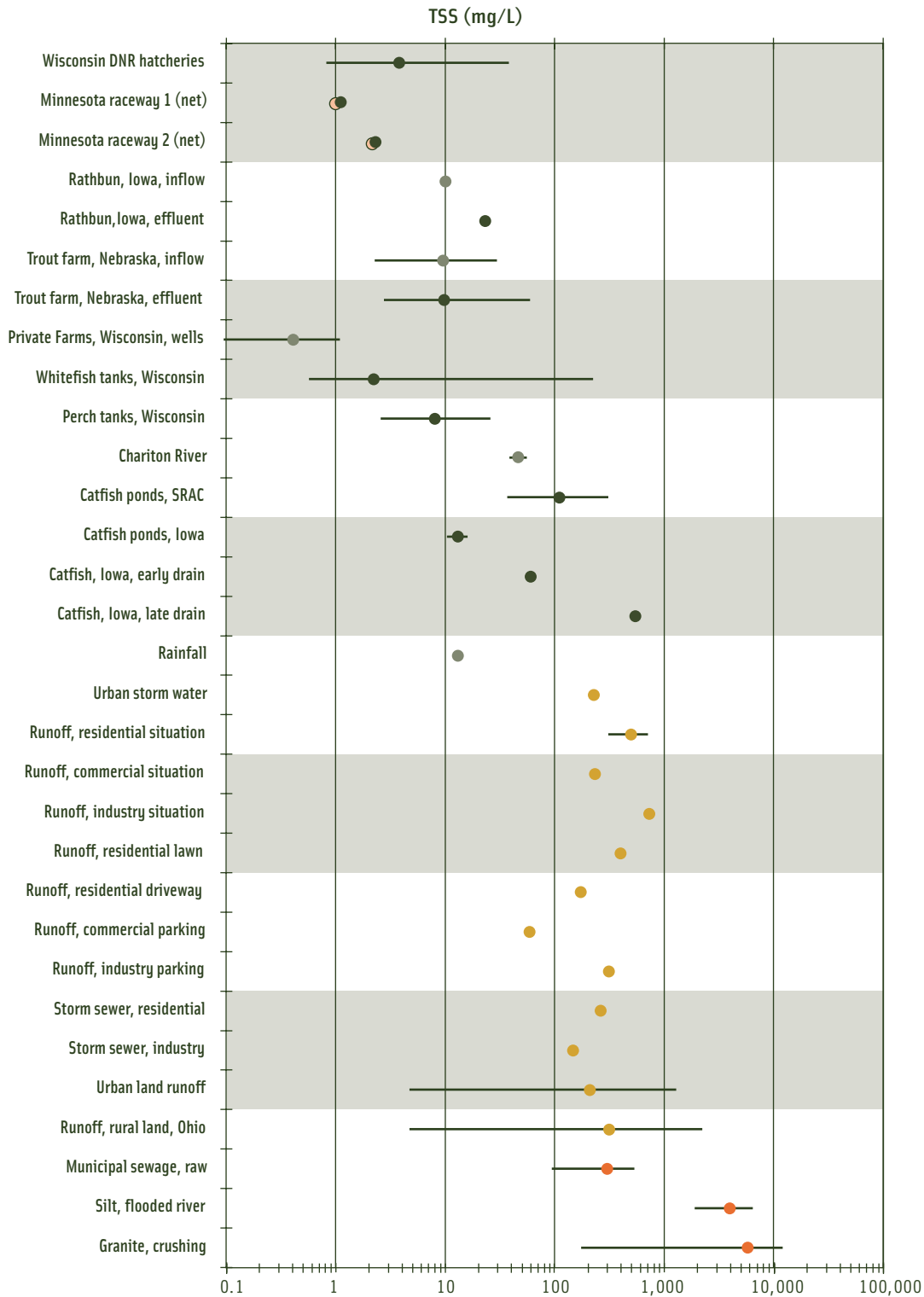
Figure 3.   Representative total suspended solids (TSS) concentrations (mg/L) of aquaculture water sources (●) and aquaculture rearing and effluent waters (●) (the shadowed dots represent the net change in concentration between the source and the effluent) in comparison with other rural and urban situations (●) and municipal sewage effluents and extremely turbid mining situations (●). Dots indicate either a reported representative value or a measure of central tendency (mean or median), and the horizontal bars indicate the high-low range of the reported values. Sources are Fair et al. 1968; McGauhey 1968; NAS 1969; Weibel 1969; Thomann 1983; Bannerman 1990; Beveridge et al. 1991; Brune and Tomasso 1991; Phillips et al. 1991; Bannerman et al. 1993; Haug 1993; NCRAC 1994; Ning 1996; Tucker 1998; and Wisconsin DNR Wisconsin Pollutant Discharge Elimination System records. (Rivera 1995 data on Wisconsin perch ponds was omitted because she reported settleable solids (ml/L) rather than total suspended solids.)

only in situations where fairly high proportions of waste consist of fairly large particles (e.g., sewage treatment plants, pond and raceway cleaning) or where turbulence holds large particles in the water column. For waste that falls from the water column more slowly due to smaller particle size or low density, TSS is a more applicable measurement. TSS and SS represent the amount of material potentially recoverable from an effluent through prolonged settling or filtration treatments.

Extremely high levels are generally associated with transient conditions involving erosion, mining, or construction (Figure 3). In the absence of turbulence, high levels of solids tend to settle from the water column. Generally, aquaculture effluents exhibit concentrations of suspended solids that are lower than much of urban and rural runoff. The upper levels for aquaculture ponds typically result from draining and harvest. In very productive pond situations, the presence of suspended algae and plankton can complicate the interpretation of suspended solid levels.

Biochemical Oxygen Demand (BOD)

BOD, sometimes referred to as biological oxygen demand, is a traditional measure of the oxygen-consuming strength of various organic wastes; it is a useful water-quality management tool for comparison of aquaculture effluents with various other agricultural and manufacturing process wastes. While aquaculture pond and flow-through effluents have BODs slightly higher than their source waters, their BOD levels are far below the degrading strength of many raw agricultural municipal and industrial process wastes, and closer to the post-treatment levels of municipal sewage (Figure 4). The notable exceptions for aquaculture by-products are the concentrated waste sludge from RASs and unused aquaculture feed, which has extreme degrading potential. Raw fish manure also has a high degrading potential similar to that of other livestock manures.

Total Ammonia Nitrogen (TAN)

Ammonia is the major toxic nitrogenous metabolic product excreted from fish in dissolved form. The commonly used colorimetric water chemistry tests determine the total amount of ammonia present and generally express it as the weight of nitrogen as ammonia. Depending on the pH and temperature of the water, a certain percentage of the total ammonia will be in the ionized nontoxic form (i.e., NH_4^+) and some will be in the highly toxic unionized form (i.e., NH_3)—the higher the pH or water temperature, the greater the percentage of ammonia remaining unionized. These amounts are generally only

determined from tables expressing the proportion of ionized and unionized ammonia of the total ammonia value at various pHs and temperatures. At typical rearing temperatures and conditions, only a small percentage of the total ammonia is unionized, but if the total is high enough, the smaller toxic portion can still be significant. Because of its toxic potential, the presence of ammonia is normally monitored and closely controlled in fish rearing by dilution or ammonia removal systems. Fortunately, microbial activity converts ammonia to a still-toxic intermediate form, nitrite, and then to nitrate, a relatively nontoxic form. Aquaculture ponds and especially RASs generally depend on microbial conversion of ammonia and nitrite to nitrate. In some cases, chemically based ammonia control is employed in high-density culture situations, especially RAS units. Ammonia levels can vary widely even in aquaculture source waters, but aquacultural rearing typically contributes ammonia beyond the background level (Figure 5). Even in highly dilute flow-through aquaculture operations, small increases in total ammonia nitrogen are observable. Much higher ammonia levels are characteristic of RAS sludge materials and raw wastes (Figure 5).

Total Nitrogen (TN)

TN measurements are conducted on digested water samples to ensure that all the various forms of nitrogen compounds are expressed. Therefore, it is probably a better indicator for measuring the overall load of nitrogenous materials. Again, the concentrations of nitrogen in aquaculture effluents are generally less than, or similar to, those of land runoff and treated sewage, and hundreds to thousands of times less concentrated than solids from RASs or raw sewage and manure (Figure 6).

Total Phosphorus (TP)

TP measurements are done on digested samples to reflect the overall amount of phosphorus present, including both dissolved and particulate matter. As with TN, background concentrations of total phosphorus in source waters used for aquaculture operations vary over a wide range; aquaculture operations typically raise the concentration slightly over the average incoming level. Compared with raw manures and RAS sludge, the aquaculture raceways and pond effluent levels of TP are hundreds to thousands of times more dilute (Figure 7). Typically, the phosphorus concentration in aquaculture pond or raceway effluent is roughly comparable with, or less than, the phosphorus concentration in various storm waters or runoff situations.

5-Day BOD Concentration (mg/L)
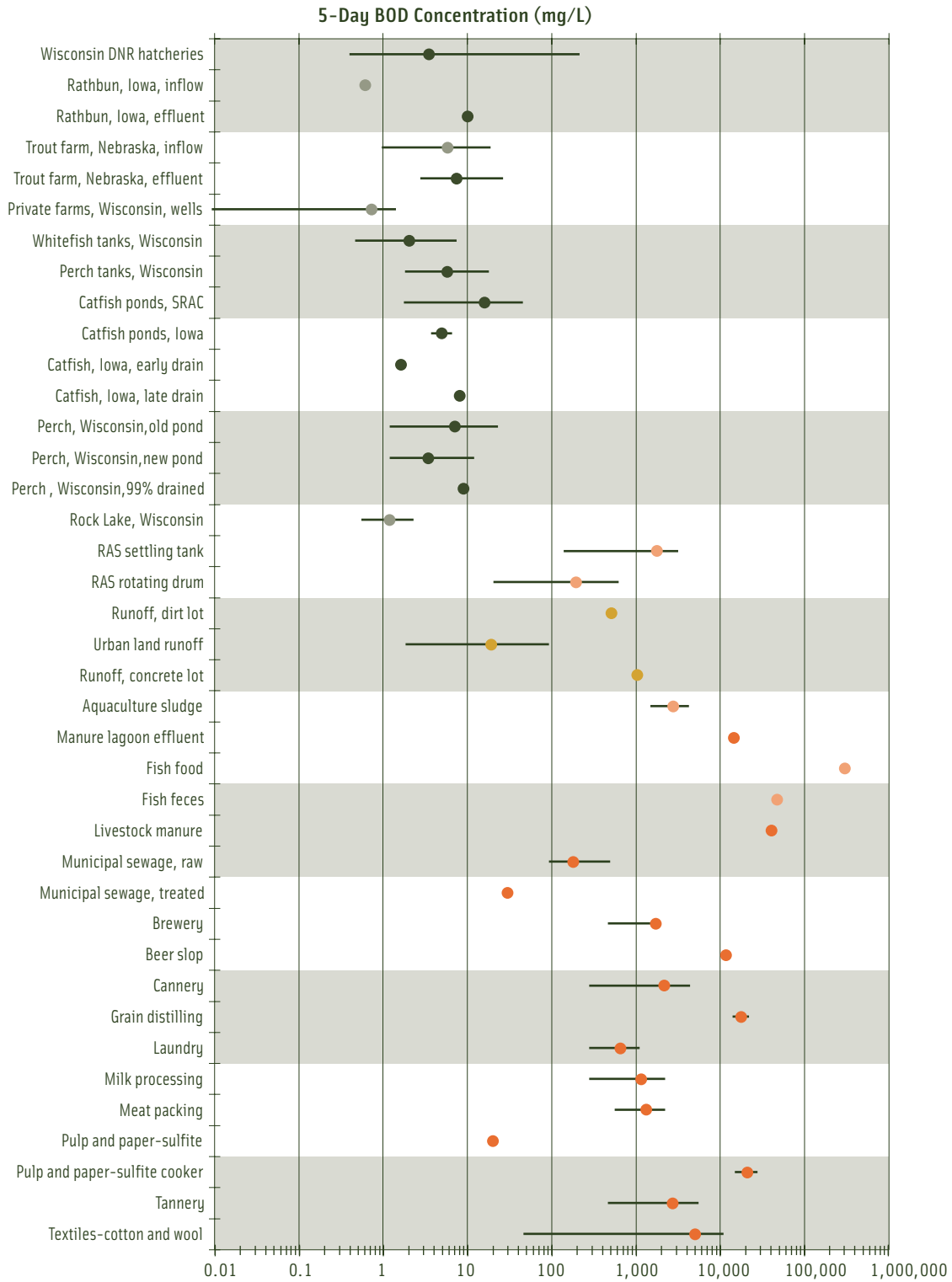
Figure 4. Representative 5-day biochemical oxygen demand (BOD) concentrations (mg/L) of aquaculture water sources (●), aquaculture rearing and effluent waters (●), and more concentrated aquaculture sludges, feeds, and fish manures (●) in comparison with other rural and urban runoff situations (●) and to municipal and industrial waste effluents (●). Dots indicate either a reported representative value or a measure of central tendency (mean or median), and the horizontal bars indicate the high-low range of the reported values. Sources are Fair et al. 1968; McGauhey 1968; NAS 1969; Weibel 1969; Thomann 1983; Bannerman 1990; Beveridge et al. 1991; Brune and Tomasso 1991; Phillips et al. 1991; Bannerman et al. 1993; Haug 1993; NCRAC 1994; Rivera 1995; Ning 1996; Tucker 1998; and Wisconsin DNR Wisconsin Pollutant Discharge Elimination records.

TAN mg/L
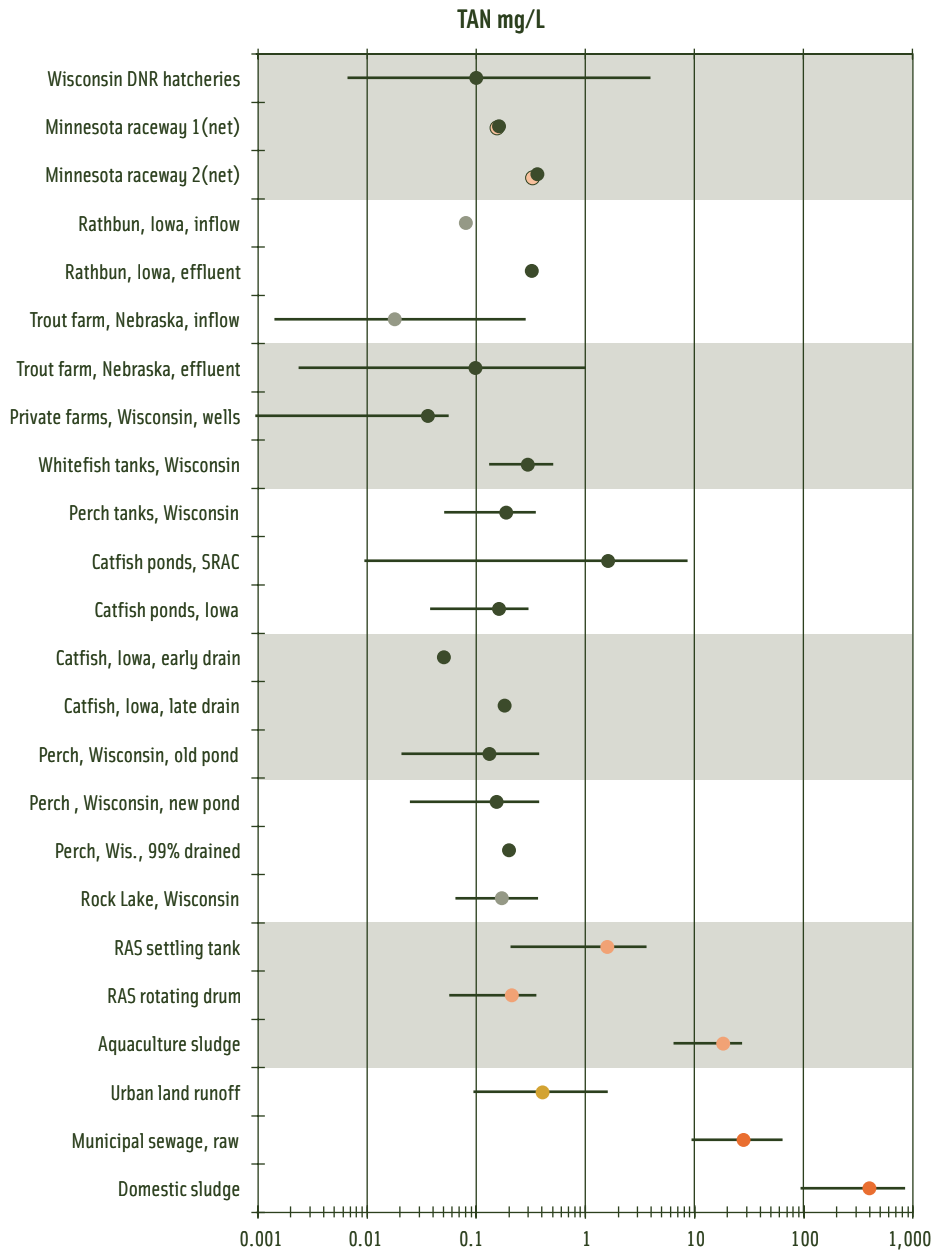
Figure 5. Representative total ammonia nitrogen (TAN) concentrations (mg/L) of aquaculture water sources (●), aquaculture rearing and effluent waters (●) (shadowed dots for Minnesota are net values of difference between inflows and outflows), more concentrated aquaculture sludges, feeds, and fish manures (●) in comparison to other rural and urban runoff situations (●), and to municipal and industrial waste effluents (●). Dots indicate either a reported representative value or a measure of central tendency (mean or median), and the horizontal bars indicate the hi-low range of the reported values. Sources are Fair et al. 1968; McGauhey 1968; NAS 1969; Weibel 1969; Thomann 1983; Bannerman 1990; Beveridge et al. 1991; Brune and Thomasso 1991; Phillips et al. 1991; Bannerman et al. 1993; Haug 1993; NCRAC 1994; Rivera 1995; Ning 1996; Tucker 1998; and Wisconsin DNR Wisconsin Pollutant Discharge Elimination System records.

TN mg/L
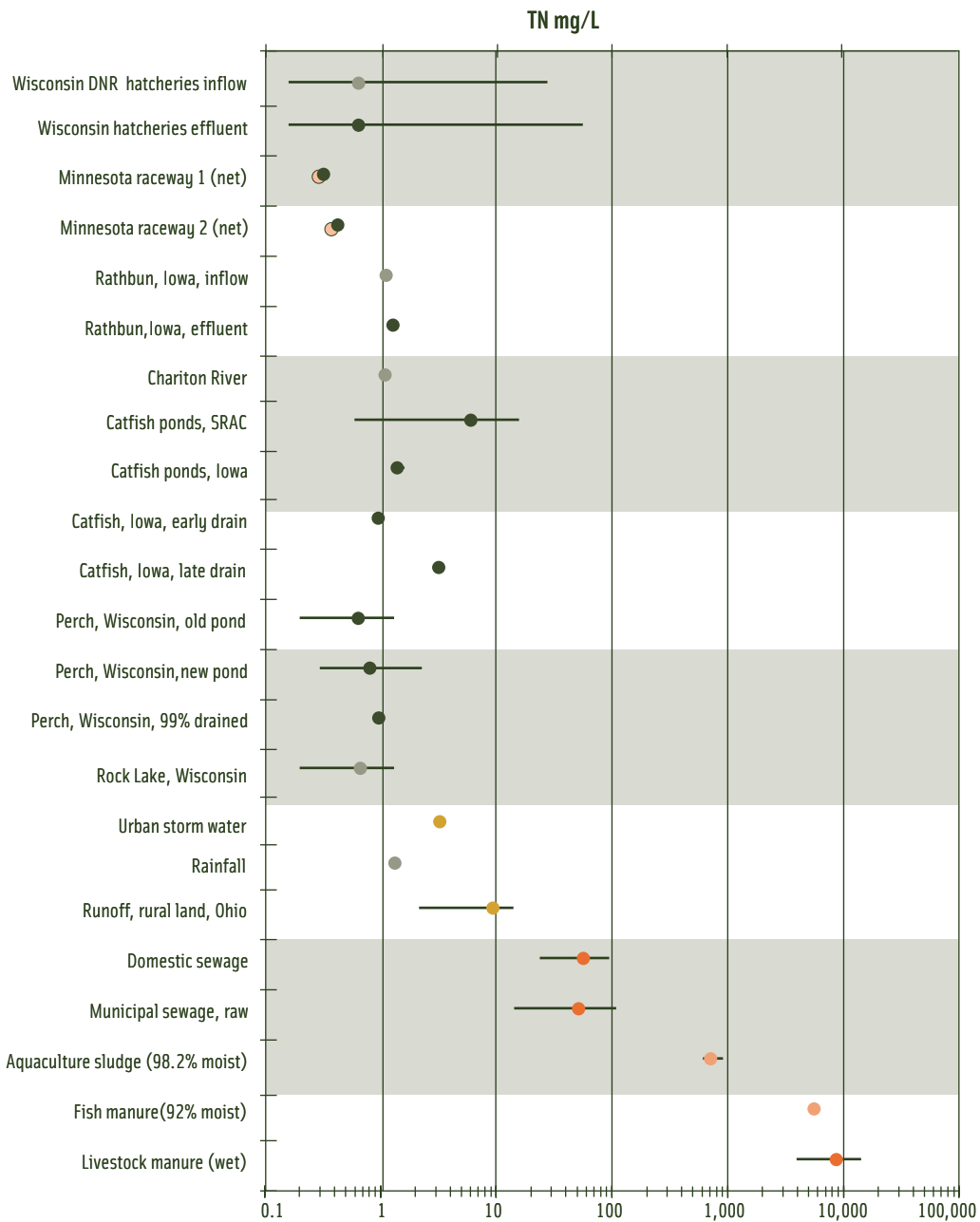
Figure 6. Representative total nitrogen (TN) concentrations (mg/L) of aquaculture water sources (●), aquaculture rearing and effluent waters (●) (shadowed dots for Minnesota are net values of difference between inflows and outflows), and more concentrated aquaculture sludges, feeds, and fish manures (●) in comparison with other rural and urban runoff situations (●) and municipal and industrial waste effluents (●). Dots indicate either a reported representative value or a measure of central tendency (mean or median), and the horizontal bars indicate the high-low range of the reported values. Sources are Fair et al. 1968; McGauhey 1968; NAS 1969; Weibel 1969; Thomann 1983; Bannerman 1990; Beveridge et al. 1991; Brune and Tomasso 1991; Phillips et al. 1991; Bannerman et al. 1993; Haug 1993; NCRAC 1994; Rivera 1995; Ning 1996; Tucker 1998; and Wisconsin DNR Wisconsin Pollutant Discharge Elimination System records.

Figure 7 (Facing Page). Representative total phosphorus (TP) concentrations (mg/L) of aquaculture water sources (●), aquaculture rearing and effluent waters (●), and more concentrated aquaculture sludges, feeds, and fish manures (●) in comparison with other rural and urban runoff situations (●) and to municipal and industrial waste effluents (●). Dots indicate either a reported representative value or a measure of central tendency (mean or median), and the horizontal bars indicate the high-low range of the reported values. Sources are Fair et al. 1968; McGauhey 1968; NAS 1969; Weibel 1969; Thomann 1983; Bannerman 1990; Beveridge et al. 1991; Brune and Tomasso 1991; Phillips et al. 1991; Bannerman et al. 1993; Haug 1993; NCRAC 1994; Rivera 1995; Ning 1996; Tucker 1998; and Wisconsin DNR Wisconsin Pollutant Discharge Elimination System records.
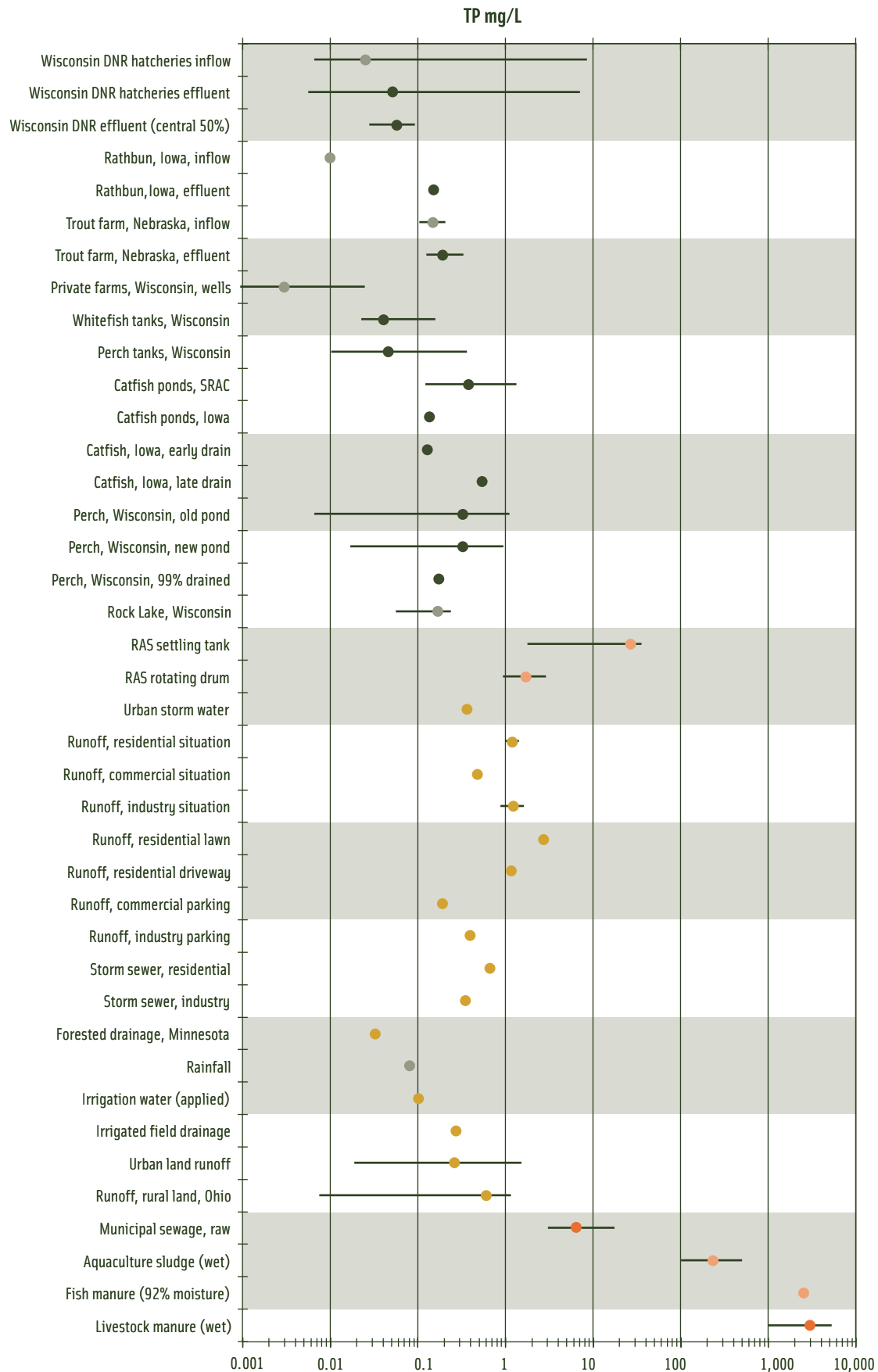
TP mg/L

Wisconsin DNR hatcheries inflow		
Wisconsin DNR hatcheries effluent		
Wisconsin DNR effluent (central 50%)		
Rathbun, Iowa, inflow		
Rathbun, Iowa, effluent		
Trout farm, Nebraska, inflow		
Trout farm, Nebraska, effluent		
Private farms, Wisconsin, wells		
Whitefish tanks, Wisconsin		
Perch tanks, Wisconsin		
Catfish ponds, SRAC		
Catfish ponds, Iowa		
Catfish, Iowa, early drain		
Catfish, Iowa, late drain		
Perch, Wisconsin, old pond		
Perch, Wisconsin, new pond		
Perch, Wisconsin, 99% drained		
Rock Lake, Wisconsin		
RAS settling tank		
RAS rotating drum		
Urban storm water		
Runoff, residential situation		
Runoff, commercial situation		
Runoff, industry situation		
Runoff, residential lawn		
Runoff, residential driveway		
Runoff, commercial parking		
Runoff, industry parking		
Storm sewer, residential		
Storm sewer, industry		
Forested drainage, Minnesota		
Rainfall		
Irrigation water (applied)		
Irrigated field drainage		
Urban land runoff		
Runoff, rural land, Ohio		
Municipal sewage, raw		
Aquaculture sludge (wet)		
Fish manure (92% moisture)		
Livestock manure (wet)		

0.001   0.01   0.1   1   10   100   1,000   10,000

TN/TP Ratio

The ratio of total nitrogen/total phosphorus (TN/TP) is one way of measuring nutrient quality and expressing the potential environmental impact and trophic response resulting from various sources of nutrient enrichment (Downing and McCauley 1992; Costa-Pierce 1995). Unlike other more desirable algae, blue-green algae can be toxic at high concentration, and some have the ability to fix atmospheric nitrogen. Because of this ability to fix nitrogen, when the TN/TP ratio is low, the plankton community can shift to an abundance of blue-green algae in eutrophic situations. Comparing TN/TP ratios, Costa-Pierce (1995) argued that average aquaculture effluent nutrients have a comparable TN/TP ratio (~5.6) to urban street drainage, human sewage, and pastureland runoff. Only a few rapidly available nutrient sources in the table appeared to have lower TN/TP ratios (e.g., septic tank effluent, eutrophic lake sediment, and gull feces) (Figure 8).

Concentrations versus Loads

Concentrations of pollutants in an effluent only tell part of the story. The total flux or loading of nutrients and waste products to the receiving waters is of primary concern in assessing potential environmental impact. Estimating loading based on end-of-the-pipe water-quality sampling alone is an expensive and laborious process. Because nutrient concentrations in both source and effluent waters and the quantity of the effluent flow itself can vary over time, frequent sampling of nutrient concentrations combined with accurate determinations of effluent and receiving water flows are required to estimate the load of a substance discharged.

The formulated diets and fertilization to sustain increased production are the ultimate sources of the loadings of organic material. Analysis of inputs (especially food and water use) can lead to a more realistic estimation of the upper constraints of aquaculture loadings to the environment. Understanding these inputs and modeling fish energetics, nutrition, and feeding efficiency to predict their fates (Cho et al. 1991, 1994; Frier et al. 1995; Cho and Bureau 1998) during the aquaculture production process is becoming recognized as a more straightforward means of assessing potential impact than attempting to reconstruct loading based on effluent sampling.

TN/TP

Figure 8. Total nitrogen/total phosphorus (TN/TP) ratios for various pollutants, and excreta and mass ratios of some aquatic organisms. To convert to molar ratios, multiply by 2.21. (Selected from Downing and McCauley 1992.)

Aquaculture Waste: Dietary Sources and Waste Reduction

The principal source of aquaculture waste is ultimately the manufactured feeds that are necessary to increase production beyond natural levels (Iwama 1991). The uneaten portion of the food has high BOD (Figure 4) and is the most direct source of waste. The excretory wastes are secondarily derived from the food that is consumed but unassimilated by the fish. The portion of the feed that is converted to fish flesh, any escaped fish, dead fish, and fish-processing waste at harvest are also ultimately derived from the feed. To prevent mortalities and manage the general rearing environment, some therapeutants (sometimes added to the feed), fertilizers, and rearing-environment management chemicals are occasionally necessary. These are wastes of the aquaculture rearing process that are separate from the food source.

To sustain a commercially viable level of production in intensive and semi-intensive aquaculture situations, feeding of formulated diets is necessary. The efficient use of feeds minimizes the unused feed remaining in rearing water. Some loss due to uneaten food is inevitable and difficult to quantify; some is due to the breakdown of pelleted feed to particles too small for the fish to consume. Although manufacturers of salmon and trout diets claim that dust content is no more than 1–2%, several measurements have shown that dust can account for as much as 3.7% (Clark et al.1985) of pelleted feed. Poor handling or storage might increase this further, but the larger proportion of the feed is presented in a suitably intact form for consumption. This suggests that most of the food that remains uneaten is a result of other factors related to feeding management and system-related factors (Beveridge et al. 1991). Estimating the amount of unused food in aquaculture operations is difficult because it is hard to separate the fecal material from uneaten food in collected waste. The few available estimates are based mostly on salmonid culture (Beveridge et al. 1991). The estimates for proportion of uneaten food ranged 1–30%. Ranges for uneaten food for tank culture of trout were 1–5%, 5–10%, and 10%–30% for dry, moist, and wet feeds, respectively, as reported by Warrer-Hansen (1982). Slightly higher estimates of 15–20% for dry feed and greater than 20% for moist feed (Braaten et al.

1983) have been reported for cage culture of salmon. Penczak et al. (1982) observed estimates of 27% and 31% for dry and moist feeds respectively, for trout cultured in net cages. Beveridge (1984) confirmed the higher feed losses in cage culture based on food conversion ratio. Beveridge et al. (1991) cited the high variability within treatments of food-loss estimates and believed it to be mainly attributable to differences in management practices and sampling methods. The particle size, surface area to volume ratio, moisture content, density, and the use of binding agents influence the settling properties and durability of uneaten food in water.

Westers (1995) makes the following recommendations for feeding and prevention of feed waste:

- The potential performance of the diet must be known for the size and species of fish. This may require labeling food with information on digestibility and waste generation, such as quantity of solids, nitrogen, and phosphorus. It could also provide information on feed conversion and growth rate obtained under controlled environmental conditions.
- The biomass of fish in the system must be known.
- The health and condition of fish must be known (appetite).
- Fish should be relatively uniform in size and capable of accepting a single-size pellet.
- Broken pellets and dust should be sifted out before feeding, and feed systems must not damage the pellets.
- Feed should be applied in a manner to maximize its consumption by fish.
- Feed should be applied at slightly below maximum ration.

Aquaculture feeds principally contain protein, carbohydrates, and lipid, with relatively minor amounts of antioxidants, vitamins, pigments, and therapeutic agents. Like other organic materials that make up solid wastes, the elemental content and relative proportions of carbon (C), nitrogen (N), potassium (K), and phosphous (P) are useful in characterizing the overall macronutrient composition. Axler et al. (1997) report the ratio of C:N:P for trout food as 43.7:6.9:1.0.

Cho and Bureau (1997) describe how dietary waste output from salmonid aquaculture can be best quantified by nutritional principles and how potential waste material can be reduced by highly digestible nutrient-dense feed formulation. The selection of highly digestible feedstuffs and the careful balancing of energy and nutrients, specifically N and P, improve retention by fish, and reduce organic matter, N, and P wastes. Gatlin and Hardy (2002) have reviewed nutritional strategies, including advancements in diet formulation, ingredient processing, feed manufacturing, and feeding

strategies that have contributed substantially to reducing the excretion of enriching nutrients, thus enhancing nutrient absorption and production efficiency in aquaculture. From 1990 to 2000, large improvements were made in reducing phosphorus and nitrogen excretion and improving protein retention of rainbow trout by altering diet formulations (Gatlin and Hardy 2002).

The use of fishmeal in diets (especially to meet the requirements of carnivorous fish, e.g., salmonids) provides highly digestible protein, but can contribute higher levels of phosphorus than are needed or can be absorbed by fish. Fishmeal use has raised criticism both because the unabsorbed phosphorus contributes to eutrophication, and, on a global scale, it has been claimed that it results in a net protein loss (Goldberg and Triplett 1997). Fortunately, most of the unabsorbed phosphorus excreted by fish is in solid form as feces or uneaten food. Rapid and efficient solid waste removal can reduce the portion of phosphorus discharged before it has the chance to leach out of the solid and become a dissolved form that is more costly and difficult to remove from effluents.

The content, solubility, and availability of phosphorus in formulated fish diets vary with the types of ingredients used. The phosphorus content of fishmeal is largely associated with the bone content, which is difficult and costly to remove. The tendency to overuse fishmeal rather than including both animal and plant protein ingredients results in higher N and P excretion, particularly in dissolved form (Cho and Bureau 1997). Substitution of lower phosphorus content plant proteins can make significant reductions in dietary phosphorus content, but can complicate problems of digestibility and waste production. Concern has been expressed over the indigestible phytin-P in plant protein ingredients. For mostly plant ingredient diets, the use of the enzyme phytase to make plant protein more digestible has been proposed. However, the practicality of this approach has been questioned (Cho and Bureau 1997) due to the instability of the enzyme during feed processing and the possibility of solubilizing more phosphorus in the solid wastes produced. A certain level of fishmeal or other animal protein that contributes some digestible phosphorus appears to be necessary for salmonids and carnivorous fish with limited digestive capacity for complex carbohydrates and perhaps for poor-quality proteins also (Cho and Bureau 1997).

Trout require between 0.55% and 0.70% available phosphorus depending on their size (Gatlin and Hardy 2002). Trout diets in 1990 typically contained twice as much phosphorus as the fish actually required. Most of the excess is absorbed and excreted in the urine in soluble form that is virtually impossible to remove from an

effluent except by plants. Fecal phosphorus excretion accounts for the balance of about 0.8% of total dietary phosphorus (Gatlin and Hardy 2002). Current trout feeds have been improved to contain 1.1–1.2% total phosphorus of which 0.7–0.9% is available. Urinary loses have been reduced by 70% and fecal losses by 50% (Gatlin and Hardy 2002).

The reduction of phosphorus is especially important to the future of flow-through and net-pen situations where the volume of water usage is too great to allow efficient dissolved phosphorus removal. Additionally, feed formulation changes will influence the issue of reduction of fishmeal in fish diets both from a phosphorus limitation and from a world ecological perspective (Goldberg and Triplett 1997). The goal in feeding should be increased efficiency, which makes sense both from an economic and an environmental point of view.

Aquaculture Waste Production in Relation to Water Use

Water Usage Comparisons

Regional aquaculture operations use only a very small fraction of regional water compared with thermoelectric cooling, irrigation, and public and industrial uses. However, aquaculture stands out in terms of usage per unit of production (Figure 9). In the south, catfish aquaculture water consumption requirements are greater than irrigation requirements per unit area for peanuts, cotton, corn, soybeans, and wheat, but comparable to or less than rice or alfalfa (Hargeaves et al. 2002). For comparison, daily human per capita domestic water usage ranges from 0.15–0.87 m^3 (40–230 gal) and averages around 0.57 m^3 (150 gal).

Even the more water conservative RASs use water on a high per ton of production basis compared with most food, chemical, and manufacturing industries (Figure 9). Flow-through aquaculture production water needs per ton of production are thousands of times higher than these industries. The high usage per level of production requirement also helps explain the dilute concentration of waste in flow-through effluent.

Water usage for flow-through culture dictate and limit, to a large extent, where future cold-water production facilities can be sited. The availability of such high-quality sites should be considered in projecting future development of this type of production system.

Waste Production Comparisons

Aquaculture is a minor producer of organic waste on a regional or national scale. Comparison with Haug's (1993) data on U.S. organic waste production helps to present a general picture (Figure 10) of aquaculture's place in the general picture of U.S. organic waste production and recovery. The combined figure for catfish and trout production from the 1997 U.S. Aquaculture census (USDA 2000) is approximately 297,000 metric tons annually. The 1997 total national aquaculture production of catfish and trout is far lower than Haug's (1993) other categories of organic waste either produced or collected on a national scale. Aquaculture waste is only a small fraction of the total fish production. Assuming a food conversion of about 1.5 metric tons of feed used per ton of fish produced and that approximately 30% of the food becomes manure, fecal material

Cubic Meters Water Usage/Metric Ton Product
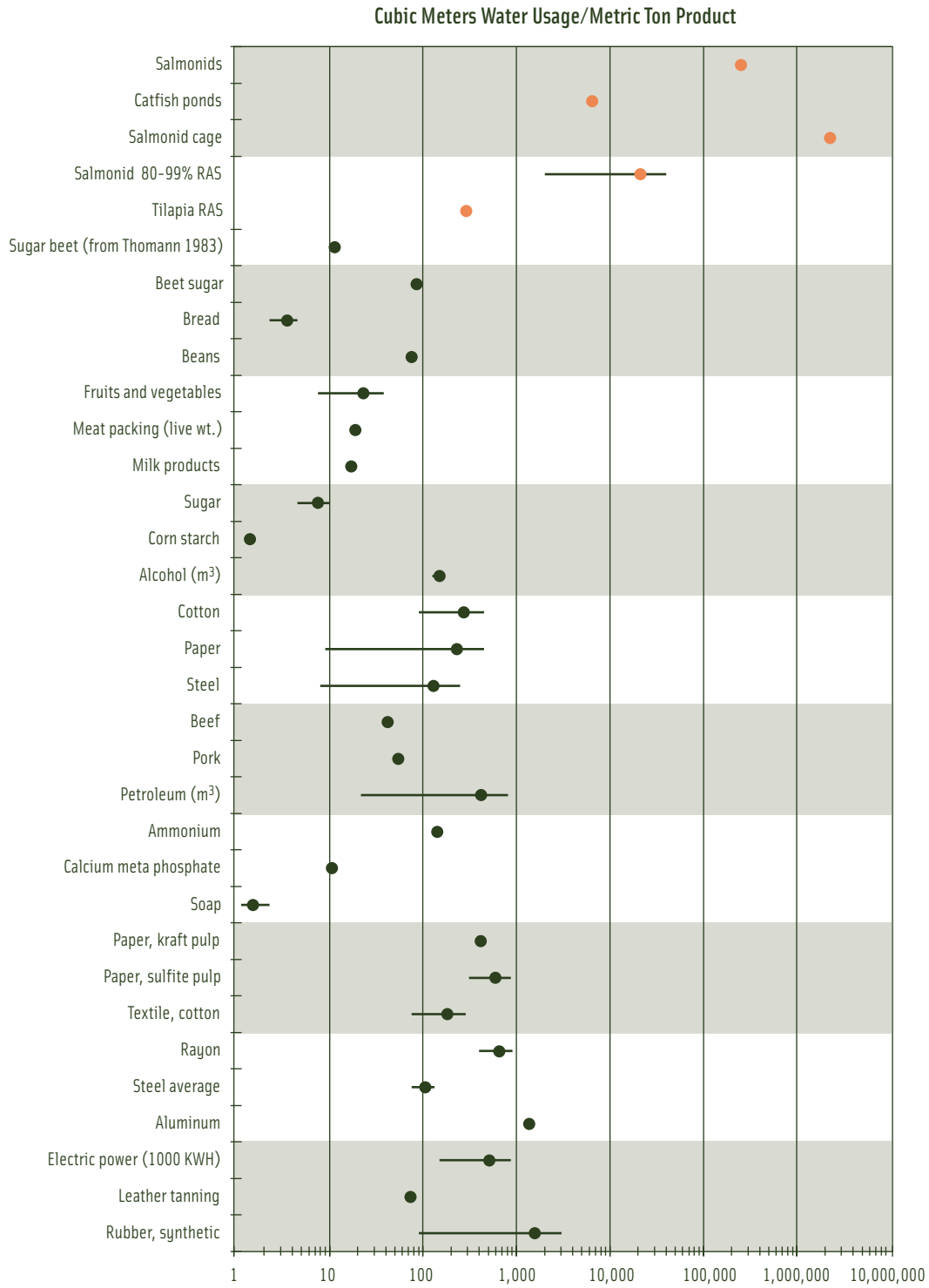
Figure 9. Comparative water usage per unit of production (metric tons, cubic meters for liquids, or 1,000s of KWH for electricity) for various aqua-cultural products (●) versus other agricultural and industrial products (●). Dots represent single reported representative values or a measure of central tendency, and the horizontal bars are high-low ranges. Sources are McGauhey (1968); Thomann (1983); Phillips et al. (1991).

U.S. Aquaculture Production versus other U.S. Organic Waste Production
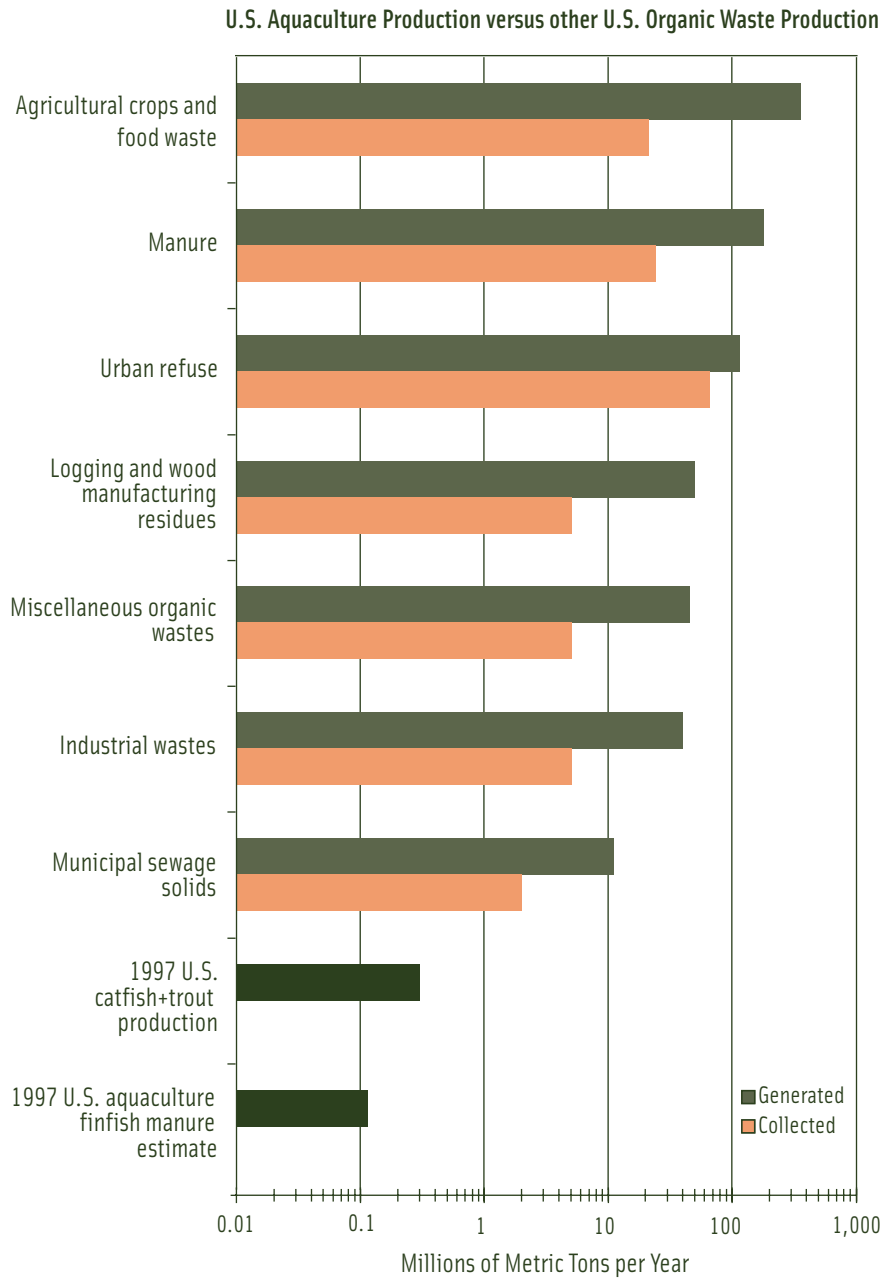
Figure 10. Estimates of organic wastes generated and collected in the United States in 1980 (after Haug 1993). For comparison, the total production of trout and catfish in the NCR in 1997 (USDA 2000) was more than an order of magnitude less than the waste generated or collected in Haug's categories. The bottom column shows an approximate estimate of annual finfish manure production based on the annual tonnage of trout and catfish produced in 1997. Units are million metric tons per year. Manure was estimated by assuming a food conversion ratio of 1.5 to estimate food used to produce trout and catfish and assuming approximately 30% of the food is converted to manure. The amount of potential collection and reuse of fish manure in the NCR is undocumented.

produced by trout and catfish would be approximately 134,000 metric tons, several orders of magnitude less than Haug's other categories.

Estimates of waste produced per metric ton of fish produced vary considerably. Westerman et al. (1993) estimated that the fecal waste produced by 23 million kg (51 million lb) of food-size trout amounted to about 10 million kg (22 million lb) (assuming 0.45 kg fecal solids per kg of trout produced). Costa-Pierce (1995) cites the Institute of Agriculture (1990) estimate that approximately 510 kg (1,124 lb) of settleable solids are produced per ton of temperate-zone, cage-cultured fish. Several additional studies have estimated the loads of various forms of waste per unit production of fish. For Minnesota raceway production with groundwater, Axler et al. (1997) estimated total annual loading rates (effluent plus sludge) per metric ton of rainbow trout production to be 289–839 kg (637–1,850 lb) for solids, 47–87 kg (104–192 lb) for nitrogen, 4.8–18.7 kg (11–41 lb) for phosphorus, and 101–565 kg (223–1,245 lb) for carbon. Figure 11 illustrates waste load per production for aquaculture from Beveridge et al. (1991).

The amount of fish manure produced and potentially recoverable for beneficial use is less well documented; amount depends to a great extent on rearing method. Most of the solids produced in pond culture are used locally for bank and levee repair, few are recovered and land applied. With current technology, net-pen solids are not recovered. Settled solids recovered from quiescent zones and settling basins of flow-through systems are typically land applied. Solids from recirculating systems are typically rapidly removed from the system in a relatively concentrated form and are either land applied or end up in sewage treatment systems.

Large amounts of manure are required to meet the nitrogen requirements of agricultural crops. While aquaculture manure can be used to beneficial effect, it is unlikely to be available in sufficient quantity to be a principal nitrogen source for regional agricultural field crops. On-site, smaller-scale agricultural ventures or noncommercial gardening seem more appropriately scaled for using aquaculture wastes.

In spite of aquaculture's currently minor role as an organic waste producer, its proximity to and use of limited high-quality water resources gives a highly site-specific potential for environmental impact. Costa-Pierce (1995) noted that there is an enormous potential for impact if effluents are discharged to enclosed basins, natural systems with low flushing rates, or vulnerable ecosystems with species of special concern. Costa-

Aquaculture Waste Loads-TSS, BOD,TN,& TP
(kg/metric ton - fish/yr) and (kg/metric ton of food used)

Figure 11. Waste loads of various representative aquaculture operations. total suspended solids (TSS) (●), biochemical oxygen demand (BOD) (●), total nitrogen (TN) (●), or total phosphorus (TP) (●) discharged per metric ton (MT) of fish production or per metric ton of food used. Salmonid values based on cited references in Beveridge et al. (1991) or Axler et al. (1997). Catfish values based on Tucker (1998) and Tucker and Hargreaves (1998) reported discharges in kg/ha from ponds with and without storage (S), assuming a production of 5,000 kg /ha.

Pierce (1995) also discussed empirical models that can be used to predict the total phosphorus in lakes based on the amount added from various sources and the relationship between total phosphorus and average summer chlorophyll level, as a measure of phytoplankton abundance. Potential differences in response to nutrient addition for oligotrophic (low-nutrient) temperate water-body situations and more eutrophic (high-nutrient) situations, like tropical pond aquaculture, were also presented. For intensive aquaculture, the major part (ca. 60–90%) of the TN in effluents occurs in the dissolved fraction, whereas the major part of TP occurs in the organic particulate fraction (ca. 60–90%) (Enell and Lof 1983; Phillips 1985). Lee et al. (1980) found that the amount of biologically available phosphorus for algal growth is 10–30% of total phosphorus. Costa-Pierce (1995) presents several tables and figures comparing phosphorus export from various land and water uses. Using data from EPA (1980), Reckhow and Simpson (1980), Costa-Pierce and Roem (1990), and Axler et al. (1996a) illustrate that phosphorus releases in units of kg TP/ha/yr from feed lots are 200–800 (178–714 lb/acre/yr); intensive salmon cage culture from 4–30 (4–27 lb/acre/yr), and intensive field agriculture from 2–18 (2–16 lb/acre/yr). They also show that mixed agricultural land, pasture land, urban land, carp culture, and catfish ponds during episodic harvest and drain events release <6 kg TP/ha/yr (5 lb/acre/yr). Phosphorus releases from precipitation, forest land, and catfish ponds during normal operation are <1 kg TP/ ha/yr (< 1 lb/acre/yr).

   Potential nutrient impact is determined by both the composition of the source and the size of the loading contributed. Typical waste loads per ton of product or per ton of food used are illustrated in Figure 11. Comparative BOD loadings (Figure 12) reported by Phillips et al. (1991) suggest that on a per-ton of product basis, aquaculture could have relatively more impact than a variety of other manufacturing processes. On a per-ton of production basis, fish manure production (Figure 13) is comparable with that of a variety of other animals, in spite of the comparatively small size of the individual animals.
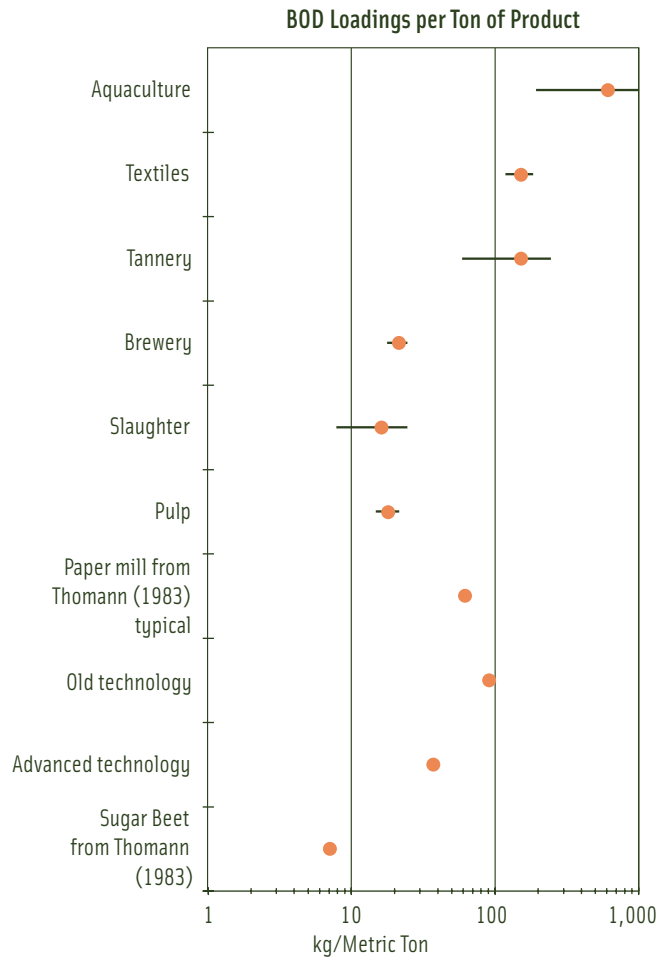
Figure 12. Comparison of biochemical oxygen demand (BOD) loadings per metric ton for aquaculture (Phillips et al. 1991) and various industrial products, suggesting that aquaculture is a relatively high water user per ton of product compared with a variety of other products. The horizontal axis is in log scale, horizontal bars represent high-low ranges of reported values, and dots represent a single representative value cited in either Phillips et al. (1991) or Thomann (1983). Thomann (1983) cited values for both older and more advanced paper manufacturing technology.

Daily Manure Production kg
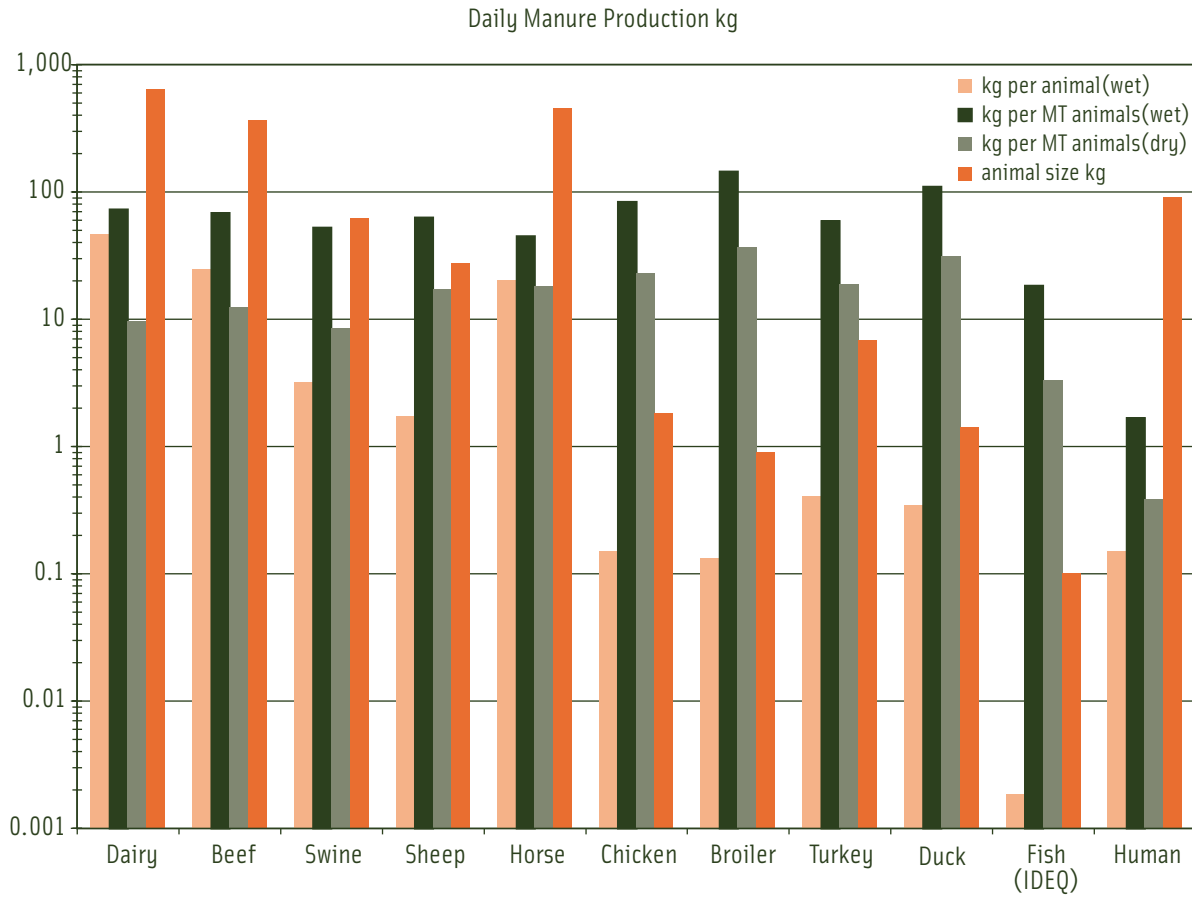
Figure 13. Comparative daily manure production in kg for agricultural livestock (ASAE Standards 1993 and Haug 1993), fish (IDEQ 1997) and humans. For each species, the wet kg manure per individual (■), wet kg manure per metric ton of animal (■), dry manure kg/metric ton (MT) of animal (■), and approximate individual organism kg size (■) are shown.

Reclamation of Wastewater and Sludge for Beneficial Use

The uneaten food, excreta, and processing wastes of aquaculture are potentially reusable materials if they can be collected in sufficient quantities in a cost-effective manner. The concentration of organic material and nutrients in an effluent, a recovered sludge, or aquatic offal can be dependent on the type of production system employed. Whereas offal is more easily collected, the recovery of concentrated usable waste from rearing water is more problematic.

Practical utilization schemes for aquaculture effluent must consider the amount, physical characteristics, and location of aquaculture wastes. The dilute nature of useful nutrients in aquaculture discharges (typical of flow-through and pond production methods) and the comparatively large water usage for fish production may confine possible wastewater recovery to essentially on-site or near-site usage of recovered wastewater. Finding an appropriately scaled application for waste may be a barrier to its reuse. Innovative thinking may be required to identify a suitable beneficial use of aquaculture wastewater and sludge.

The main constraints to use of aquaculture sludge will be matching available amounts with needs from both a quantity and location perspective, and meeting regulatory requirements. These considerations will bear heavily on the cost-effectiveness of the intended use.

There are important differences in types of wastes. In principle, recovery and reuse of waste generated through aquacultural production have much in common with the broader societal problem of waste disposal and reuse. Because disposal and beneficial reuse of municipal sewage waste is a complex societal problem, sewage sludge has received, and continues to receive, a great deal of study. Complete reference texts and extensive reviews and bibliographies (among them are Golueke 1977; Torrey 1979; Haug 1993; Outwater 1994; NRC 1996) are available on this general topic. An aquaculturist interested in the potential recovery and use of aquaculture wastes can glean a great deal of information by examining these materials because the concepts and issues involved are principally similar. It may seem expedient to dispose of aquaculture sludge at public treatment works, but mixing it with municipal waste may lower its quality for potential reuse.

The beneficial use of reclaimed municipal wastewater and sludge raises public health concerns because of the presence of toxic

contaminants and human pathogens. In the NRC (1996) review of the use of reclaimed water and sludge in food crop production, the issues and background of this topic are examined in detail. Industrial and municipal wastes and urban runoff (Bannerman et al. 1983; EPA 1983; Bannerman 1990) are likely to contain a varied assemblage of residual materials that can be toxic or of health concern, including heavy metals, polycyclic aromatic hydrocarbons, bacteria, and pesticides. Concerns over sewage sludge have lead to the U.S. Environmental Protection Agency (EPA) rules for land application of wastewater and sludge, testing procedures, and definitions of sludge quality. Sludges may have to undergo costly testing to meet regulatory standards. Nevertheless, municipal sludge has been directed to a wide variety of beneficial uses, including land application as fertilizer to crops for human consumption, nursery and landscape crops, grasslands and forests ,and to reclaim land damaged by mining. It has even been incorporated into poultry feed. Aquaculture sludge, like other animal manures, could serve any of these uses with less concern for human health and general toxicity.

Aquaculture effluents and sludge are more similar to other animal manures than to municipal or domestic sewage. Like other animal manures, aquaculture sludge is less likely to have significant levels of toxic contaminants if handled separately, than when it is diverted to public treatment works where it is mixed with municipal and industrial waste. Although aquaculture sludge is less likely than raw municipal sewage to harbor human pathogens, manures may carry the risk of spreading diseases associated with their animal host, as well as residues of theraputants used to treat these diseases. The risk of antibiotic residues developing resistant bacteria or the transference of disease to humans merits further investigation.

Beneficial Use and Treatment Technologies for Effluent Wastewater

Aquaculture Effluents in Irrigation. The NRC (1996) report on the use of reclaimed water and sludge in food crop production reviews the issues surrounding the use of reclaimed municipal wastewater for irrigation purposes. Irrigated cropland in the United States grew from 7.7 million ha in 1945 to more than 20 million ha in 1978 and dipped to 18.8 million in 1987. Much of the nation's water withdrawal is used for crop irrigation. For instance, in 1990, crop irrigation accounted for 518 million m^3/day of water or 41% of all fresh water withdrawn for all uses from well and surface water (Solley et al. 1993).

Because aquaculture operations of a flow-through or outdoor pond type tend to be sited where water is abundant, it may be unlikely that they are near sites with a high demand for irrigation. Additionally, the timing of water release by an aquaculture operation is not necessarily going to correspond to water demand for irrigation. Because effluents contain potentially elevated levels of nutrients, they might seem to have fertilizing properties, but highly diluted nutrient levels usually mean that only the water itself and not its nutrient content is of practical use for plant growth. In a recent SRAC project (Tucker 1998), the use of aquaculture pond effluent for soybean irrigation was investigated. Irrigation itself was found to have a beneficial influence, but the nutrient content did not measurably affect soybean yield.

Readily available alternative water sources and low effluent nutrient concentrations combined make it unlikely that reclaiming aquaculture effluent for irrigation purposes will become a widely used method of recovery in this region. However, there may be specific circumstances where such a technique could be beneficially applied.

Wetlands for Waste Treatment. Constructed wetlands have been used for waste treatment in a wide variety of applications, including treatment of domestic septic, small-scale municipal, and agricultural waste by-product situations. Extensive bibliographies on their construction and use are available through the USDA Water Quality Information Center of the National Agricultural library, as well Kadlec and Knight (1996).

Before constructed wetlands can become a feasible waste reclamation solution for aquaculture operations, consideration has to be given to the nutrient concentration and the potential volume of the discharge. Estimated hydraulic residence times are lengthy for effective removal of nutrients by wetlands (Adler et al. 1996e). In consequence, the high-volume dilute discharges of typical flow-through type operations will require vast adjacent acreage of wetland. The SRAC pond effluent project (Tucker 1998) evaluated wetland use and recommended a four-day hydraulic residence time. Recommended hydraulic residence times of 7–10 days for wetlands constructed in colder, more northern regions require even greater amounts of acreage. Typical midwestern flow-through operations with flows from hundreds of thousands to several million gallons per day are unlikely to have the necessary acreage available for the recommended residence time. Constructing large enough wetland systems for the full in-line flow of such operations is unlikely to be economically feasible.

In aquaculture situations where the discharge is more nutrient-concentrated and less voluminous (e.g., RASs), it may be possible to justify the construction of wetlands similar to those recommended for treating individual household septic waste systems and

dairy or animal processing wastewater. Wetlands might be properly scaled for a flow-through operation if waste flow is diverted to a lesser volume side-stream waste flow or the overflow from off-line settling basins. For nearly static pond-rearing situations with more limited periodic discharge during storm events, draining, or harvest activities, wetland treatment may be more feasible. Axler et al. (1996b) proposed a wetland to treat recovered waste from Minnesota salmon net-pens, but the operation closed down before it could be fully tested. For aquacultural operations that collect and concentrate wastes, such as rotary filter or bead filter washings from RASs, a small constructed wetland might be effective in recovering waste nutrients and fine solids. However, these same systems might be better matched with aquaponic systems.

Vegetative Buffers. Vegetative buffers are currently used for erosion control and the treatment of storm runoff from agricultural fields, construction sites, and urban environments. Vegetative buffers allow for the trapping of suspended solid materials and the reduction of nutrients discharged into streams. Unlike constructed wetlands, they are not intended to receive a continuous flow. Instead, they address situations of episodic storm water flows. Buffer strips can be somewhat smaller in scale than wetlands and still achieve some protective benefit. Specifically, the harvest- and cleaning-event effluents associated with pond overflows and pumped/siphoned removal of settled waste from raceways might benefit from being diverted through vegetative buffer areas that could allow some trapping of suspended solids and infiltration of nutrient-burdened wastewater.

Episodic aquaculture discharge situations associated with harvest and cleaning of ponds or raceways are similar to storm water drainage events where vegetative buffer strips, grass-lined channels, and infiltration ponds are used to prevent the discharge of high levels of suspended solids and nutrients into streams and rivers. Control of the volume of flow applied to such buffer strips is important to maintaining their effectiveness.

The recent SRAC effluent project (Tucker 1998) investigated the use of grass filter strips for treatment of rearing pond effluent. Suspended solids, organic matter, and TN were lowered in catfish pond effluent using overland runoff through established strips of Bahia or Bermuda grass. When the suspended solids concentration was low (<30 mg/L), the filter strips were not effective in filtering solids. They were most effective when the solids concentration in the effluent was >200 mg/L. For situations between 30–200 mg/L of solids, these strips removed as much as 50% of the solids. The SRAC project (Tucker 1998) recommended further study to determine the lifetime and efficacy of this technique over extended periods.

The U.S. Department of Agriculture and the National Agricultural Library Water Quality Information Center have compiled extensive bibliographies on riparian vegetative buffer strips. In addition, regional state extension programs have numerous publications on buffer strips, e.g., Iowa State University Extension Service.

Aquaponics. There has been much interest in the use of aquaponics, or hydroponic soil-less greenhouse culture, of vegetable and fruit crops (Resh 1989) as a means of recovering dissolved nutrients from recirculating aquaculture systems (McMurtry et al. 1990, 1993a, b; Rakocy et al. 1992; Adler et al. 1996 a-d; Singh et al. 1996). While constructed wetlands and vegetative buffer strips are designed to treat effluents to improve water quality and protect natural habitat, hydroponics crops are produced for profit as well as to remove nutrients from the rearing system. This type of production requires sophisticated knowledge of both the fish-rearing system and the hydroponics system, as well as knowledge of the fish and plant growth requirements. The fish effluent by itself does not necessarily supply all the required nutrients for plant growth. The recent work of Adler et al. (1996a-d) holds great promise for beneficial recovery of aquaculture waste. They used the luxury consumption of phosphorus by young plants to overcome problems with growth, as the concentration of phosphorus in the growing solution is reduced by plants to below the optimal levels for further growth. Older plants that had benefited from earlier luxury phosphorus uptake were able to continue absorbing more phosphorus in the increasingly lowered concentration of the rearing solution. Using a conveyor strategy, they have been able to reduce phosphorus levels to consistently <0.01 mg/L without a reduction in crop productivity or quality. Goldberg and Triplett (1997) report highlighted eight recirculating aquaculture firms; five of which were reported as having some type of vegetable crop associated with their production system. Of those listed, S&S Aquafarms of West Plains, Missouri, is within the NCR. Also, Archer Daniels Midland, Inc., has invested in an operation linking tilapia and greenhouse vegetable production in Illinois.

Beneficial Use of Aquaculture Solids and Sludge

In general, once it is collected and removed from the rearing system, fish manure poses potential benefits and difficulties that appear to be similar to those of other manures. Fish manure can provide organic content to soil, which is beneficial to moisture retention. However, the nitrogen levels (2–5% dry matter, Westermann et al. 1993) are not as high and readily available to the plants as is the case with inorganic soluble nutrients. Also, fish waste solids may

not contain the proper balance of nutrients for plant growth, and further addition of nutrients may be required to sustain profitable growth.

Land application has become the easiest and most widely adopted technique to recycle solids from hatchery settling ponds. If properly applied, this technique safely disposes of waste while providing crop fertilization and improving or maintaining soil structure. The nutrient characteristics and fertilizer value of fish manure have been found to depend on the source materials, the methods of collection and storage, and the methods of land application (Harris 1981; Mudrak 1981; Smith 1985; Willet and Jacobsen 1986; Olson 1992a, b; Westerman et al. 1993; Axler et al. 1997; Naylor et al. 1999). Based on 1991 trout production levels of 23 million kg for the United States, it has been estimated (Westerman et al. 1993) that about 10 million kg of fecal solids are available and should be removed from raceway waters before they are discharged. Solids samples showed substantial variation between farms and between types of manure management on the same farm. The length of time trout manure was stored influenced the quality. With regard to heavy metal content, zinc levels have been found to be slightly high, but not high enough to be limiting to land application.

To avoid environmental damage, land application of aquaculture waste slurry should take into account site conditions, timing of application, application rates, crop type, crop uptake capacity, crop rotation, and land availability for application (IDEQ 1997). IDEQ (1997) published guidelines for removal and land application of aquaculture waste solids that are especially appropriate for large-scale, salmonid-type operations. The amount of wastes generated from even a large aquaculture facility, however, will benefit only a relatively small amount of cropland, when properly applied. One hundred acres of land are adequate to accommodate biosolids produced by a properly operated aquaculture facility with a swimming inventory of 453,600 kg (1 million lb), feeding 6,804 kg (15,000 lb) of fish feed per day (IDEQ 1997).

For the typically smaller NCR operation, the potential nutrient benefit of aquaculture waste to cropland is generally too small to provide incentive for its incorporation into field crop management planning. Smaller scaled alternatives may provide more appropriate "beneficial" uses. For smaller scale horticultural, landscape, or gardening application, further processing and stabilization of raw waste by composting is probably justifiable for handling, storage, and marketing reasons. Williams and Starr (1990, 1995) pointed out important constraints on the regional use of fish manure. Surface land application of this material can produce undesirable odors. Also, during winter the frozen soil surface prevents the waste from being incorporated into the soil, consequently creating problems with loss through spring runoff.

Storing this material for later disposal presents formidable economic constraints. Williams and Starr (1995) reported that Michigan Department of Natural Resources estimated costs for constructing fish waste storage facilities for state of Michigan fish hatcheries to range from $0.08–0.13/L ($0.30–$0.50/gal), as compared with estimated costs of $0.01–0.02/L ($0.05–$0.07/gal) for land application with subsurface injection. At those rates, an aquaculture facility producing 45,360 kg (100,000 lb) of fish per year may have to spend up to $75,000 for a waste storage facility and up to $15,000 per year in disposal costs.

Settled fish waste is generally in the form of a slurry that is about 95% water. While this high water content can be beneficial for direct land application, dewatering of the sludge for further storage may be needed to reduce the space required and to alleviate storage and handling costs. Williams and Starr (1990, 1995) studied the further dewatering of fish production waste using a filter press system. The filter press with the aid of fly ash, agricultural lime, diatomaceous earth, or perlite reduced the moisture content and produced a filter cake material that retained 95% of the N, P, and BOD demand, while reducing the moisture content of the waste by about 35%.

Preliminary attempts to assess the value of the filter cake material as a fertilizer for impatiens *(Impatiens wallerana)* plant growth (Williams and Starr 1995) were not very promising. Although the filter cake contained nutrients, their quantity or availability did not compare with similar volumes of inorganic fertilizer, causing decreased growth rates. The fine particle size of the filter cake may have decreased pore space of the growth media, reducing growth rate. The agricultural lime used to aid filtration resulted in lime levels two to three times higher than the maximum recommended as a root medium. The filter cake material resulted in a high pH that may also have been detrimental to the growth of the plants at the incorporation rates used.

Composting offers an alternative to direct land application. Conventional composting is an accelerated bio-oxidation of organic matter passing through a thermophilic stage (45–65˚C) (113–149˚F) where microorganisms (mainly bacteria, fungi, and actinomycetes) liberate heat, carbon dioxide, and water. Advantages of composting are that it helps to stabilize the waste materials, reducing odor, BOD, and the volume of the waste. Composting produces a useful soil amendment or planting medium that provides a slow-release fertilizer and increases water-holding capacity. The more stabilized finished compost is easier to store and transport for use than raw waste, and application can be delayed for better

coordination with crop needs. Composting is also suitable for processing dead fish, spoiled feed, and fish processing residues (UWSGI 1992; Fornshell et al. 1998). Composts have a commercial value and can potentially be sold as a soil amendment. Compost microflora have been shown to have plant disease suppressive qualities (Adler et al. 1996f). Potential constraints on composting include storing wastes for considerable time and extra expense before they can be used. The conventional compost pile requires considerable bulk in order to retain the heat required for the thermophilic reaction, and in the NCR, outdoor composting is subject to reduced activity during the cold season.

Vermicomposting is an alternative to conventional composting that uses worms (Edwards and Neuhauser 1988) in the composting process. Vermicomposting offers several advantages that may be valuable for NCR aquaculturists. Vermicomposting is also a bio-oxidation and stabilization process of organic material that, in contrast to conventional composting, involves the joint action of earthworms and microorganisms and is less dependent on a thermophilic stage. The earthworms are the agents of turning, fragmentation, and aeration, consequently avoiding some of the labor required for the turning of bulky conventional compost piles. The end products are the worms themselves, valuable either as bait or as live fish food, and a highly valued specialty organic soil amendment (Edwards and Burrows 1988). Earthworms can break down a wide range of organic wastes and are commercially bred on a large scale in organic wastes for fish bait.

Currently, other livestock manures are used as feedstock for worms, and there is reason to believe that either recovered aquaculture biosolids in the form of fish manure, unused feed, or fish processing waste could be effectively processed through vermicomposting. This technique is still undergoing further testing. Idaho studies suggest that a gradual acclimation (Rynk et al. 1998) of the worms to feeding on fish manure may be required. Continuing investigation of vermicomposting using bead filter clarifier sludge from a yellow perch RAS at the University of Wisconsin-Milwaukee has found that when wet sludge was fed in appropriate amounts it was readily accepted, achieved excellent worm growth, and performed as well or better than a commercial worm-growing diet when fed to red worms and African nightcrawlers in established indoor worm beds.

Although vermicomposting is an ecologically sound and attractive means of converting waste to beneficial by-products, marketing and commercial sale of worms and compost should be approached with caution. The relatively short worm life cycle permits worm populations to potentially proliferate exponentially, but finding markets for selling worms can be as or more problematic than producing the worms themselves. Potential worm growers should be especially cautious of high-priced "contract buy-back" operations with overly optimistic projections of worm demand. While buy-back operations in other types of contract farming can and have been operated honestly, there is a history of unscrupulous "Ponzi"-type investment schemes in the worm industry, in which money from later contract sales is temporarily used to pay back early contracts, until the bubble bursts. It is advisable to investigate potential markets for worms and vermicompost as fully as possible and to know whether the buy-back company has a market for worms beyond selling to the next investor. Starting small and developing local or niche markets on your own may be a viable alternative.

Beyond the marketing problem, potential constraints on conventional composting and vermicomposting involve storing wastes for considerable time and extra expense before they can be used. Outdoor composting is subject to reduced activity during our regional cold season.

Toward Environmentally Sound Regional Aquaculture Development

Like other general environmental impacts due to urbanization, industrialization, and intensive agriculture, aquaculture's potential benefit needs to be objectively weighed against its potential detrimental impact. Aquaculture in our region is currently a minor waste producer. However, based on examples of rapid aquaculture growth, especially overseas, there is the concern that if it should develop in a rapid, uncontrolled fashion it would have detrimental impacts similar to what historically occurred due to urban, industrial, and agricultural development in our region. The likelihood of similar unregulated expansion in our region is minimized through an existing framework of environmental regulations.

Further aquaculture development will create increased demand for increasingly limited clean water resources. To a degree, aquaculturists can proactively move toward sustainability and lessen concern by employing practices that reduce water usage and waste production and that divert recoverable wastes to beneficial use.

Rubino and Wilson (1993) recognized the tradeoffs of "sustainable development":

"Sustainable development has become a concept that everyone supports but no one defines consistently. Yet, the concept gets to the heart of the issues upon which the future of aquaculture depends. Sustainable aquaculture can be defined by culture practices that husband the natural resource base, limit environmental impacts, and provide for profitable long-term production (see Folke

and Kautsky 1989). A sustainable aquaculture industry hinges upon reconciling environment and development tradeoffs. As in any use of natural or environmental resources, there are tradeoffs between food production, economic profitability, risk, and environmental preservation."

Recommendations

The following are proactive measures that aquaculturists can take to promote and ensure the minimization of environmental impact and development of more sustainable aquaculture practices for our region.

- Develop and employ water-conserving rearing strategies, including greater levels of water recirculation, such as partial recirculation in cold-water flow-through hatcheries as well as the intensive recirculation systems for cool-water and warm-water fishes.

- Develop, demonstrate, and promote efficient feeding management techniques and nutrient-efficient diet formulations that reduce nutrient waste loads and facilitate rapid solids removal.

- Design new tank and raceway facilities with rapid solids removal and recovery in mind with techniques such as double drains, settling, and side-streaming of solids. Find economical means of retrofitting existing facilities.

- Emphasize and refine the development of feeding and biological-process-based budgeting models of aquaculture waste production as a more cost-effective way of dealing with aquaculture waste load estimation than costly end-of-the-pipe water-quality sampling.

- Demonstrate and evaluate the cost-effectiveness of integrated waste recovery and reuse strategies, especially those that provide the possibility of secondary crops that may improve the economic return of aquaculture operations.

Glossary

acre. A unit of area equal to 43,560 ft^2, 4047 m^2 or 0.4047 hectares (ha).

acre-foot. Amount of water needed to cover an acre to a depth of one foot; it is equal to 43,560 ft^3.

algae. Simple photosynthetic plants with unicellular organs of reproduction and not possessing true roots, stems, or leaves.

ammonia. A nitrogen compound that occurs as a colorless, relatively dense, pungent gas that has the chemical formula NH_3 (unionized) or NH_4^+ (ionized); the ionic form is also known as ammonium.

ammonia-nitrogen. When ammonia concentrations are referred to as ammonia-nitrogen, only the nitrogen part of the compound, which is only 63.6% of the ammonia concentration, is being referenced. To convert ammonia-nitrogen to ammonia, multiply by 1.57.

aquaculture. Farming of plants and animals that live in water, e.g., fish, shellfish, and algae.

aquaponics. An integrated fish culture and plant hydroponics production system.

aquifer. A geological formation or structure that stores or transmits water, such as to wells and springs. Use of the term is usually restricted to those water-bearing formations capable of yielding water in sufficient quantity to constitute a usable supply for people.

Bahia or Bermuda grass. A stoloniferous southern European grass (*Cynodon dactylon*) often used as a lawn and pasture grass. In the context of this report, a grass used for vegetative buffer or infiltration strips.

baitfish. Term used to describe a multitude of fish species typically used for bait in fishing.

Best Management Practices (BMPs). Management practices, developed pursuant to federal water-quality legislation, to minimize or prevent water pollution. Often, in more general usage, referring to any good environmental stewardship practices.

biochemical oxygen demand, BOD (or biological oxygen demand). The amount of oxygen required for the biochemical degradation of organic matter and the oxygen used to oxidize inorganic materials such as sulfides and ferrous iron initially present in a sample. BOD determination is an empirical test in which standardized laboratory procedures are employed; typically, the incubation period of the sample is five days at 20°C. When chemicals have been added to the water to inhibit the oxidation of ammonia (nitrification), the results are reported as carbonaceous biochemical oxygen demand or CBOD.

biofilter. A growth of bacteria colonies on a media surface over which water passes to remove nutrients and break down toxic nitrogenous metabolites in the water. Used as an essential part of most water recirculation systems and also sometimes for treatment of outlet water from a farm to reduce waste loadings entering a river or stream.

biomass. The amount of living matter in an area or system, including plants and animals.

biotic index. An aggregated number, or index, based on several attributes or metrics of an aquatic community that provides an assessment of biological conditions.

buffer strip, vegetative. A gently sloping area of vegetation that runoff water flows through before entering a stream, storm sewer, or other receiving system. The buffer strip may be an undisturbed strip of natural vegetation or it can be a graded and planted area. Vegetative buffer strips act as living sediment filters that intercept and detain storm water runoff. They reduce the flow and velocity of surface runoff, promote infiltration, and reduce pollutant discharge by capturing and holding sediments and other pollutants carried in the runoff water.

carbohydrates, complex. A large group of starches, celluloses, and gums that contain carbon, hydrogen, and oxygen in similar proportions. They get their name from their complex, chainlike structure. During digestion, starches are typically broken down into sugars and used by the body for energy.

carbon dioxide and bicarbonate. Produced as a result of respiration by fish and other aerobic organisms (including plants) in the system. Carbon dioxide has the effect of increasing the acidity of the water. It is present in three different forms in the water: CO_2 (free carbon dioxide, which is toxic to fish), HCO_3^- (bicarbonate ion), and CO_3^- (carbonate ion). The concentration of each is dependant on the pH of the water.

central tendency. Statistical measures of central tendency or central location are numerical values that are indicative of the central point or the greatest frequency concerning a set of data. The most common measures of central location are the mean, median, and mode.

composting. Controlled microbial degradation of organic waste, yielding an environmentally sound product with value as a soil amendment.

constructed wetlands. A constructed wetland is "a designed and man-made complex of water saturated substrates, emergent and submergent vegetation, animal life, and water that simulates natural wetlands for human use and benefits" (from *Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural*. 1989. D.A. Hammer, ed. Lewis Publishers, Inc. Chelsea, Michigan).

crop uptake capacity. The capacity of a crop to utilize land-applied nutrients without resulting in excessive application that impairs water quality.

cubic meter (m^3). Metric measure of volume useful in describing water discharge and usage. A cubic meter of water is equivalent to 264 gallons or 35.3 cubic feet.

denitrification. Biochemical conversion of nitrate (NO_3) to nitrite (NO_2), ammonia (NH_3), and free nitrogen (N), as in soil or aquatic systems by microorganisms.

dewatering. Removal of excess water from the solid wastes generated during the wastewater treatment process.

effluent. Wastewater or other liquid – raw (untreated), partially, or completely treated – flowing from a reservoir, basin, treatment process, or treatment plant.

empirical models. Models relying upon or derived from observation or experiment. (Capable of proof or verification by means of observation or experiment.)

end-of-the-pipe water-quality sampling. Sampling of effluents at the point that they are discharged to the receiving water. This type of sampling may not necessarily consider the process generating the effluent or the impacts on the receiving system. Understanding pollutant loadings by this method requires that the sampling scheme be designed to take into account the nature and timing of the production process.

enzyme. Any of numerous proteins produced by and functioning as biochemical catalysts in living organisms.

episodic storm event. One of a series of related events in the course of continuous account.

eutrophication. Complex sequence of events in a water body initiated by nutrient enrichment; that is, an increase in trophic state.

fecal material. Excrement or waste material excreted from the bowels of animals.

fertilization. In the context of this report, the application of fertilizer to boost the productivity of biological production systems.

fertilizer. Any of a large number of natural or synthetic materials, including manure and nitrogen, phosphorus, and potassium compounds, spread on or worked into soil to increase its fertility.

filter cake material. In the context of wastewater treatment, this is the partially dewatered layer of biosolids that accumulates on the filter surface.

filter strips. A buffer/filter strip is a vegetated area adjacent to a water body (i.e., river, stream, wetland, lake). The buffer/filter area may be natural, undeveloped land where the existing vegetation is left intact, or it may be land planted with vegetation. Its purpose is to protect streams and lakes from pollutants such as sediment, nutrients, and organic matter; prevent erosion; and provide shade, leaf litter, and woody debris. Buffer/filter strips often provide several benefits to wildlife, such as travel corridors, nesting sites, and food sources.

fishmeal. A high-protein food ingredient manufactured from desiccated and finely ground fish, generally small fish of lesser value as whole products.

flow-through. In the context of aquaculture rearing systems, this term refers to those in which water is continuously exchanged to maintain water quality.

full-flow volume. The entire flow of a raceway or hatchery. In terms of water treatment, full-flow water treatments require much larger holding capacity than smaller side-streamed waste flows.

groundwater. (1) Water that flows or seeps downward and saturates soil or rock, supplying springs and wells. The upper surface of the saturated zone is called the water table. (2) Water stored underground in rock crevices and in the pores of geologic materials that make up the Earth's crust.

infiltration. Entry of water from precipitation, irrigation, or runoff into the soil profile.

ionized. An atom or group of atoms that has acquired a net electric charge by gaining or losing electrons from an initially electrically neutral configuration.

kg. A kilogram or 1,000 grams. Equivalent to 2.2 pounds.

kilowatt hour (KWH). A unit of electrical consumption equal to the total energy developed by one thousand watts acting for one hour.

land application. A process or activity involving the application of wastewater or semiliquid material to the land surface for the purpose of disposal, pollutant removal, fertilization, irrigation, or groundwater recharge.

load or loading. Amount of a substance entering the environment (soil, water, or air). Reported as weight of material transported during a specified time period, such as tons per year.

macronutrient. Major nutrients including nitrogen, phosphorus, carbon, oxygen, sulfur, and potassium.

mean. The arithmetic average of a set of observations, unless otherwise specified.

median. The middle or central value in a distribution of data ranked in order of magnitude. The median is also known as the 50th percentile.

metabolism. The chemical and physical processes necessary to maintain life that occur with every living organism .

metabolites. Substances produced or resulting from metabolic processes.

milligrams per liter (mg/L) = ppm (parts per million). A unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water; equivalent to one part per million.

nitrate. An ion consisting of nitrogen and oxygen (NO_3^-). Nitrate is a plant nutrient and is very mobile in soils. Formed as a result of the breakdown of ammonia to nitrite and then to nitrate by bacteria (see nitrification). May also be present in watercourses through run-off from the addition of nitrate as fertilizer to agricultural land.

nitrification. Biochemical oxidation of ammonia (NH_3), ammonium (NH_4^+), or atmospheric nitrogen (N) to nitrate (NO_3) or nitrite (NO_2).

nitrite. An ion consisting of nitrogen and oxygen expressed as NO_2^-. Toxic chemical formed during the oxidation of ammonia to nitrate by bacteria during nitrification. As the conversion of ammonia to nitrate occurs in biological filters, most of the nitrite is converted to nitrate before the water exits the filter.

nitrogen, available. Amount of nitrogen present as either nitrate or ammonium, forms which plants can readily absorb.

nitrogen, total (TN). The total amount of nitrogen available in a sample.

nitrogen, total ammonia (TAN). The nitrogen portion of the total ammonia present (63.6% of the total ammonia concentration).

nonpoint source. Source of pollution in which pollutants are discharged over a widespread area or from a number of small inputs rather than from distinct, identifiable sources. Compare to **point source**.

nutrient. A chemical that is an essential raw material for the growth, development, or maintenance of an organism.

nutrients, dissolved. Nonfilterable soluble nutrient content of water. Nitrogen and phosphorus are difficult to remove from wastewater by conventional treatment processes because they are water soluble and tend to recycle.

off-line settling. An effluent treatment system that uses only a small portion of the full-rearing flow to remove the biosolids from individual rearing units to a specifically designed effluent settling pond that receives only the smaller cleaning or side-stream flow.

pH. A measure of the relative acidity or alkalinity of water. Water with a pH of 7 is neutral; lower pH levels indicate increasing acidity, while pH levels higher than 7 indicate increasingly basic solutions.

phosphorus. Nonmetallic element. In water, phosphorus occurs almost solely as phosphates. The forms are classified as orthophosphates, condensed phosphates, and organically bound phosphates. They occur in solution, in particles or detritus, or in the bodies of aquatic organisms. An essential element for living organisms, phosphorus is often the limiting nutrient in relation to algal blooms and plant growth. An excessive amount released into the environment can, therefore, increase the plant growth in lakes and streams.

phosphorus, acid hydrolyzable. The fraction of the phosphorus, containing the "condensed" phosphate, converted to orthophosphate by acid hydrolysis at boiling water temperature.

phosphorus, available. Amount of phosphorus present in a form that can be readily taken up by plants.

phosphorus, dissolved. Phosphorus fraction remaining in a filtered water sample.

phosphorus, organic. Phosphate fraction converted to orthophosphate by oxidation destruction of the organic matter in the sample.

phosphorus, reactive. Phosphorus as orthophosphates that respond to colorimetric tests without preliminary hydrolysis or oxidative digestion of the sample. Reactive phosphorus can be either dissolved or suspended.

phosphorus, suspended. Phosphorus from the fraction retained on the filter. Generally determined by difference between total P and dissolved P.

phosphorus, total (TP). The total amount of reactive acid hydrolyzable and organic phosphorus available in a sample following hydrolysis and oxidative reduction of the water sample.

phytin-P. Most of the stored P in plants is found in seeds, mainly as phytin P (PP). Phytin-P is poorly available to monogastric animals, and this availability varies both within and between ingredients.

point source. Source of pollution that is distinct and identifiable, such as an outfall pipe from an industrial plant.

polycyclic aromatic hydrocarbons (PAH). A group of more than 100 different chemicals that are formed during the incomplete burning of coal, oil, gas, garbage, or other organic substances like tobacco or charbroiled meat.

Ponzi or pyramid-type investment scheme. An illegal investment structure in which the funds of new members are used to pay off old investors.

quiescent area. A portion of a rearing tank or raceway that is devoid of fish and has a low enough turbulence to allow the settling of biosolids.

raceway. A channel or tank with continuous flow of water constructed or used for high-density fish production.

receiving waters. Bodies of water that receive runoff or wastewater discharges, such as rivers, streams, lakes, estuaries, and groundwater.

recirculating aquaculture system (RAS). A rearing system that reuses its water and employs clarifiers, aeration devices, and biofilters to maintain water quality. Water usage is generally restricted to make up loses due to waste siphoning, back washing of filters, evaporation, etc.

recirculation system, partial. Rearing systems that reaerate and reuse a portion of their hatchery flow but still rely on a higher level of water exchange to maintain water quality, especially with regard to nitrogenous waste build-up, rather than biofiltration processes.

retention time or residence time. The amount of time it takes for the entire water body to be replaced; calculated by dividing the lake volume by the rate of discharge or outflow. Also called replacement time or flushing rate.

runoff. That part of the precipitation, snowmelt, or irrigation water that appears in uncontrolled surface streams, rivers, drains, or sewers.

septic tank. Sewage disposal tank in which a continuous flow of waste material is decomposed by anaerobic (in the absence of oxygen) bacteria.

side-stream. The diversion of a smaller portion of the total rearing system water flow, generally for cleaning or water-treatment purposes.

sludge. The settleable solids separated from liquids during processing; the deposits of foreign materials on the bottoms of streams or other bodies of water.

solids, settleable (SS). That portion of the solids that can be removed by settling in a specified period of time.

solids, total dissolved (TDS). Concentration of all substances dissolved in water (solids remaining after evaporation of a water sample). TDS is a water-quality parameter defining the concentration of dissolved organic and inorganic chemicals in water. After suspended solids are filtered from water and water is evaporated, dissolved solids are the remaining residues. Conductivity, usually expressed in units of microsimens, formerly micromhos or in mg/L, thus becomes an indirect measure of the level of impurities in the water.

solids, total. The total amount of solids in the sample, including dissolved, suspended, and volatile.

solids, total suspended (TSS). A fixed volume of sample is filtered through a preweighed and washed glass fiber filter. The filter is then rinsed and dried at 103˚–105˚ C. The change in the weight of the filter represents the weight of suspended materials.

species, exotic. Species occurring in a given place as a result of direct or indirect, deliberate, or accidental actions by humans. Synonyms are alien, introduced, nonnative, and nonindigenous.

species, invasive. Official term for an exotic species whose introduction can cause economic or environmental harm, or harm to human health.

species, nuisance. Undesirable plant or animal species. Commonly exotic or invasive species.

species, transgenic. This term describes an organism that has had genes from another organism put into its genome through recombinant DNA techniques. These animals are usually made by microinjection of DNA into the pronucleus of fertilized eggs, with the DNA integrating at random.

subsurface injection. The land application of biosolids sludge by injecting the sludge beneath the soil surface.

suspended solids. Solids that are not in true solution and can be removed by filtration. Such suspended solids usually contribute directly to turbidity. Defined in waste management, these are small particles of solid pollutants that resist separation by conventional methods.

sustainability. Meeting the needs of the present without compromising the future; emphasizing and maintaining underlying ecological processes for the long-term productivity of goods, services, and values, without impairing productivity of the land.

ton. A metric ton is 1,000 kilograms or 2,200 pounds. A U.S. gross or long ton is 2,240 pounds or 1.016 metric tons. A U.S. net or short ton is 2,000 pounds or 0.907 metric tons. A U.S. shipping ton is equal to 40 cubic feet of cargo. A British shipping ton is 42 cubic feet of cargo. A register ton for measuring internal capacity of a vessel is 100 cubic feet.

trophic state. Characterization of a body of water in terms of its position along a continuum of biological productivity ranging from oligotrophic (low productivity) to eutrophic (high productivity).

turbidity. The amount of solid particles that are suspended in water and that cause light rays shining through the water to scatter. Thus, turbidity makes the water cloudy or even opaque in extreme cases. Turbidity is measured in nephelometric turbidity units (NTU).

vermicomposting. The processing of organic waste using earthworms to help stabilize the waste and producing worm castings and compost as an organic soil amendment.

vermiculture. The culture and farming of worms with the worms as the primary product, with worm castings as a secondary product and not necessarily involving the processing of waste materials as worm food.

winterkill. Massive die-offs of many species of fauna in a body of water due to conditions of low oxygen content or anoxia during the winter.

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