Categories of Recirculating Aquaculture Systems

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Abstract

This paper presents a systematic categorization of recirculating systems based upon their ecological mimicry. Although natural aquatic systems are almost endless in their variation of physical and chemical characteristics, recirculating systems are normally designed to approximate only their most fundamental aspects. The authors' proposed classification system based on the most basic divisions with respect to a system's salinity, temperature, and trophic state would permit the definition of integrated system design criteria for the vast majority of aquaculture applications. Specialization of systems based upon pH regimen may also be justified in a few specialized cases. The proposed classification system identifies twelve combinations of temperature (warmwater or coldwater), salinity (marine or fresh), and trophic status (oligotrophic, mesotrophic, or eutrophic). The trophic states are assigned water quality criteria that reflect a blend of natural and recirculating conditions that are normally observed. Of the 12 possible combinations, 9 categories seem to represent the vast majority of recirculating aquaculture systems, and would appear to justify development of broad criteria. One additional system class that falls outside the basic structure because of its pH constraints seems worthy of addition, bringing the total number of practical categories to 10. Common names are assigned to the 10 categories to represent their natural counterpart or function. These names mask the underlying rationale for development, but should facilitate their adoption by the aquaculture community. The establishment of a classification system will facilitate the development of treatment strategies and design criteria in support of the various recirculating categories. Comments on the draft classification system are being encouraged by posting of the criteria in the Internet at <http://la-sea-grant.lsu.edu/recirculatingsystems/Recirqua/RecirquaDefault.htm>. Refinements will be made in response to comments prior to final publication.
Introduction

Over the last decade the unit processes required for treatment of recirculating systems have been clearly defined (Lucchetti and Gray, 1988; Huguenin and Colt, 1989; Rosenthal and Black, 1993). The four most critical processes are aeration (oxygen), clarification (solids, BOD), biofiltration (BOD, ammonia, nitrite), and degasification (carbon dioxide). Systems with extended hydraulic retention times must generally have an alkalinity replenishment regime to compensate for the alkalinity-consuming nitrification reaction. Additional treatment components including denitrification (nitrate, alkalinity), ozonation (BOD, color), disinfection (pathogens), and foam fractionation (surfactants) are provided to comply with specific production needs.

The rationale for implementation, including both device selection and sizing criteria, vary widely (Parker 1981; Kaiser and Schmitz, 1988; Losordo and Westeman, 1994; Heinen, et al. 1996; Arbib and Van Rijn, 1995; Summerfelt, 1995; DeLosReyes and Lawson, 1996; Twarowska et al. 1995). In fact, there are so many combinations of technologies that the industry is caught in a development eddy. Clearly, some assemblies of technologies are more reliable and cost effective than others. However, each system design is virtually unique; yet, there are so many variations in purpose, device interactions, and water quality objectives that it is difficult for meaningful advancements to be recognized. While individual treatment devices display a high level of technological refinement, integration of technologies for cohesive treatment packages is faltering.

This paper proposes a recirculating classification system with the intent that the classification system will serve as a foundation for the systematic generation of integrated design criteria. Focused refinement of integrated designs with respect to reliability and cost minimization will increase the prospects for profitable operations by avoiding unnecessary capital and operational costs, an essential feature in the cost-sensitive aquaculture area (Muir, 1981; Losordo and Westeman, 1994). The following section presents the underlying rationale for selection of the parameters utilized to conduct the initial partitioning of the production systems.

Classification Scheme

In reviewing the diversity of recirculating systems, it becomes apparent that they vary widely according to the water quality objectives. The water quality divisions can be clustered according to level of organic loading or trophic level: the lightly loaded systems displaying the best water quality, and the heaviest loaded systems representing the worst across a wide band of water quality variables. Additional resolution can be obtained by examining the temperature and salinity regime appropriate for the species cultured. In a few cases, there is further refinement according to the pH or alkalinity of the system. Impact on the design of treatment systems was the primary rationale used for inclusion or exclusion of these potential classification parameters.
Trophic Level

The concept of trophic level is used in the classification of lakes to distinguish the level of nutrient enrichment (Holm, 1977; Wetzel, 1983). Nutrient loading generally controls the level of algal growth in the lake, and thus, controls the productivity of the food chain in the lake. The cleanest lakes, as estimated by areal nutrient loading, are classified as "oligotrophic". Oligotrophic lakes tend to be very clear and hold the most pristine waters, but low productivity levels restrict fish populations. As a lake ages, internal cycling of nutrients from the sediments builds up, the lake becomes very productive, supporting algal growth, healthy zooplankton populations, and ultimately, a robust fish population. These lakes are classified as "mesotrophic" or moderately enriched. As nutrient loading levels increase further, the system becomes "eutrophic" indicating that the productivity is so high that the system displays water quality instability. This is evidenced typically by algal blooms, dissolved oxygen crashes, and intermittent ammonia peaks. Only tolerant fish species tend to prosper in a eutrophic environment.

By analogy fish production systems can be categorized as oligotrophic, mesotrophic, or eutrophic by the level of the water's enrichment as driven by the feed application rates. There is a general trend towards water quality deterioration as feed loading increases. However, in this case, the classification is more closely associated with the water quality objectives rather than the feed loading since the treatment components can be sized to partially offset loading, invalidating the use of a strict loading guideline. The best water quality conditions are associated with the oligotrophic systems, and the worst with the eutrophic systems.

A classification system with at least three levels appears to be a justifiable refinement of earlier attempts to establish general water quality criteria for aquaculture (e.g., Rogers and Klemetson, 1985). In all cases, the water quality criteria are selected to assure a relatively stress-free environment (Tomasso, 1996) for the cultured species and to meet the production objectives.

Oligotrophic recirculating systems, with their excellent water quality (Table 1), are most frequently used for breeding purposes. Valuable broodstock are often held at low densities with oversized treatment units to assure stress-free development. For example, the best water quality is often demanded for shrimp maturation (Lawrence and Hunter, 1987). Eggs and fry of many species are very sensitive to water pollution and most parameters must be held below detection limits. Similarly, display aquaria are often kept in an oligotrophic state to assure that the highest aesthetic standards are met. Recirculating soft-crab (Callinectes sapidus) shedding systems (Malone and Burden, 1988a) and soft-crawfish (Procambarus clarkii and P. zonangulus) shedding systems (Malone and Burden, 1988b; Malone et al. 1996) are designed to display oligotrophic conditions to protect the animals as they pass through the vulnerable molting process. In some cases, sensitive species must be kept in oligotrophic conditions throughout their life.

The mesotrophic classification describes the bulk of high-density production systems where risk and economics must be carefully balanced to achieve profitability (e.g., trout [Salmo gairdneri] - Heinen et al. 1996; Kaiser and Schmitz, 1988); tilapia [Oreochromis niloticus] - DeLosReyes, 1996; Twarowska et al. 1995). Here some deterioration in aesthetics is permitted and water
quality is held at safe levels to avoid growth inhibition and disease problems. Dissolved oxygen levels are frequently permitted to drop to 5 mg/L, and total ammonia nitrogen (TAN) and nitrite nitrogen (NO₂-N) are allowed to fluctuate to as high as 1 mg-N/L, a level widely recognized as tolerable for growout of most food species. Deterioration in water color and turbidity is permitted as these parameters are weakly correlated to fish health. Total suspended solids levels (and the associated BOD) are allowed to creep up to about 15 mg/L, just below the level that may be of damage to the more sensitive species, and below the level where biofouling problems begin to occur within pipes and treatment components.

Table 1: Water quality standards are proposed for each trophic level allowing engineers to more appropriately develop integrated design guidelines.

<table>
<thead>
<tr>
<th>Water Quality Parameter</th>
<th>Oligotrophic</th>
<th>Mesotrophic</th>
<th>Eutrophic</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dissolved Oxygen (mg/L)</td>
<td>&gt;6.0</td>
<td>&gt;5.0</td>
<td>&gt;4.0</td>
<td>Essential, low levels induce stress, reduce growth, or kill</td>
</tr>
<tr>
<td>Carbon dioxide (mg/L)</td>
<td>&lt;1.0</td>
<td>&lt;5.0</td>
<td>&lt;25</td>
<td>High concentrations impact respiratory processes and can reduce pH to levels that inhibit nitrifiers</td>
</tr>
<tr>
<td>Total Ammonia (mg-N/L)</td>
<td>&lt;0.3</td>
<td>&lt;1.0</td>
<td>&lt;2.0</td>
<td>NH₃ toxic, high levels reduce growth, induce stress, or kill</td>
</tr>
<tr>
<td>Nitrite (mg-N/L)</td>
<td>&lt;0.3</td>
<td>&lt;1.0</td>
<td>&lt;2.0</td>
<td>Toxic, induces respiratory stress and kills</td>
</tr>
<tr>
<td>Nitrate (mg-N/L)</td>
<td>&lt;50</td>
<td>&lt;200</td>
<td>&lt;500</td>
<td>Toxic to some ornamental and marine species</td>
</tr>
<tr>
<td>Biochemical Oxygen Demand (mg-N/L)</td>
<td>&lt;5.0</td>
<td>&lt;10</td>
<td>&lt;20</td>
<td>Contributes to biofouling and promotes bacterial blooms that can contribute to stress.</td>
</tr>
<tr>
<td>Total Suspended Solids (mg/L)</td>
<td>&lt;5.0</td>
<td>&lt;15.0</td>
<td>&lt;25.0</td>
<td>Contributes to biofouling, causes gill damage in sensitive species</td>
</tr>
<tr>
<td>Turbidity (NTU)</td>
<td>&lt;1</td>
<td>&lt;10</td>
<td>&lt;100</td>
<td>Aesthetics, clear water helps with disease prevention and management</td>
</tr>
<tr>
<td>pH</td>
<td>&gt;7.0*</td>
<td>&gt;7.0</td>
<td>&gt;7.0</td>
<td>Low pH can inhibit nitrifying bacteria in biofilters</td>
</tr>
<tr>
<td>Alkalinity (mg-CaCO₃/L)</td>
<td>&gt;80*</td>
<td>&gt;80</td>
<td>&gt;80</td>
<td>Low alkalinity can inhibit nitrifying bacteria in biofilters</td>
</tr>
<tr>
<td>Color (abs. @ 436 nm)</td>
<td>&lt;0.1</td>
<td>&lt;0.3</td>
<td>Not Applicable</td>
<td>Aesthetics, caused by inert refractory organics</td>
</tr>
<tr>
<td>Hardness (mg-CaCO₃/L)</td>
<td>Not Applicable</td>
<td>Not Applicable</td>
<td>Not Applicable</td>
<td>Can be important to cultured species, but has little impact on design</td>
</tr>
</tbody>
</table>

* A pH range of 5.0-7.0 and alkalinity of <80 mg-CaCO₃/L applies to "Tropical Rain Forest" category only.
The eutrophic category exists for the growout of the most tolerant species [e.g., carp (Cyprinus carpio) - Arbiv and Van Rijn, 1995; snakehead (Channa striatus), Qin et al. 1997; Kemp’s ridley turtles (Lepidochelys kempi) - Malone et al. 1990; alligators (Alligator mississippiensis) - DeLosReyes et al. 1995] that show vigorous growth under moderately deteriorated water quality conditions. Here, dissolved oxygen levels are allowed to drop to an economic optimum level usually defined through net growth studies. For example, Papoutsoglou and Tzibas (1996) demonstrated a least-cost oxygen level of 3.8 mg/L for blue tilapia (Oreochromis aureus) in recirculated water. The toxic compounds ammonia and nitrate are allowed to rise to 2 mg-N/L, below the level adversely impacting growth or inducing chronic disease for tolerant species (Qin et al., 1997). Aesthetic and convenience criteria are nearly abandoned at this level with the water allowed to literally become opaque due to turbidity (<100 NTU) and color. Suspended solids (<25 mg/L) and BOD₅ (<20 mg/L) are not allowed to rise to the level where heterotrophic domination limits biofiltration (Harremoes, 1982; Rogers and Klemetson, 1985; Zhang et al. 1995). Despite the relatively low standards for water quality set for eutrophic production conditions, a number of species, having presumably evolved under similar natural conditions, can prosper under these conditions.

In summary, it appears that a three-tier division of recirculating systems is well justified. Three divisions are sufficient to reflect the diversity of system qualities without becoming burdensome. Careful attention needs to be given to the establishment of the water quality standards associated with each classification, assuring that one parameter does not effectively limit the breadth of application of the classification.

**Temperature**

Further subdivision of the classification system by temperature appears mandatory. Temperature impacts the rates of chemical and biological processes at the most fundamental level. Of primary concern are the metabolic rates of the species cultured and of bacterial populations traditionally used to purify recirculating waters. A simplistic two-step classification between coldwater (<15 °C) and warmwater (>15 °C) is proposed to allow rational sizing of components whose efficiencies are impacted by temperature. In the case of oxygen, for example, this would allow engineers to make sizing adjustments to compensate for changes in the saturation level and transfer constants induced by temperature (Huguenin and Colt, 1989). Areal nitrification in biofilters are generally believed to decline with temperature, impacting the surface area requirements for treatment of a given load (Sharma and Ahlert, 1977; Knowles et al. 1965; Sma and Baggaley, 1975; Wortman and Wheaton, 1991).

Although temperature responses of individual species of fish, crustaceans, and mollusks has been generally studied, the more global relationship between temperature and metabolic activity across species is much more vague owing to the evolutionary variations in enzymatic systems. Thus, it cannot be assumed that the gross metabolic level of a coldwater system is less than that of a warmwater system, although clearly some elements such as the biofiltration unit will be adversely impacted. Given this state of affairs, a simple division of systems into a coldwater and warmwater classification seems appropriate, however, further subdivisions may be justified as temperature effects on integrated designs become better known.
Salinity

Salinity has a major effect on the saturation level and transfer kinetics of oxygen. As the salinity level increases, maintenance of a selected oxygen level becomes more difficult. It is also recognized that foam fractionator performance improves with salinity, whereas, clarifiers which depend on settling may be adversely impacted. The impact on biofiltration units is not clear, although evidence of significant differences has been presented (Nijhof and Bovendeur, 1990). The impact of salinity on gas transfer alone justifies a division between marine (>10 ppt) and freshwater (<10 ppt) applications, but does not seem to justify an intermediate brackish water classification.

Alkalinity and pH

From a water quality perspective, waters are often described as acidic (<7.0), neutral (7.0), or alkaline (>7.0) on the basis of the hydrogen ion concentration. Alkaline waters are dominated by hydroxide ions, and acidic waters by hydrogen ions. The pH can have a major impact on the rate of chemical and biological reactions. The principal impact on system design relates to biofiltration design, and more specifically the impact of pH on bacterial activities. As a general statement, both heterotrophic and nitrifying bacteria are inhibited by low pH. The critical nitrifying bacteria are clearly impacted by either low pH or low alkalinity (Sharma and Ahlert, 1977; Paz 1984). A significant decline in nitrification kinetics occurs at pH values just below neutral, usually in association with alkalinites below 80 mg-CaCO₃/L.

From an engineering perspective, pH is a volatile parameter since it is also defined by the ratio of carbon dioxide and the bicarbonate ion concentration in most applications. Once the carbonate alkalinity of a system is defined, the pH fluctuates with the carbon dioxide level. It may be more appropriate to classify recirculating systems by their alkalinity as acidic (<80 mg-CaCO₃/L) or alkaline (> 80 mg-CaCO₃/L) under the presumption that only low alkalinity systems can display low pH values. An exception can be induced by a poor degasification component. However, acidic (low alkalinity) systems are rare, being used primarily for the breeding of South American rain forest ornamental species (Weaver, 1991). These systems can have pH levels as low as 5.0, and are almost always oligotrophic. Acidic systems are rarely used outside of this unique application area. Instead, even rainwater species are reared in systems with pH values near 7.0, where bacterial kinetics are much more favorable and biofiltration requirements are greatly reduced.

Acidic conditions are not naturally conducive to growth, thus, repartitioning based on a pH or alkalinity does not seem justified. Establishment of a unique classification to support the production of rain forest ornamental fish, however, is warranted by the economic impact of this industry (Chapman et al. 1997).
Hardness

Hardness is technically a measurement of the cumulative concentration of the divalent cations commonly found in water. In most aquaculture applications it primarily reflects the calcium ion concentration. Calcium is an important water quality parameter with waters frequently being classified as hard (high calcium levels) or soft (low calcium levels). Although a number of recommendations exist for the maximum or minimal hardness levels for a variety of species, hardness has little or no impact on the majority of treatment devices used in recirculating systems. Partitioning of the recirculating systems according to hardness would serve little function in the generation of design criteria.

Recirculating System Classifications

Review of the significant partitioning parameters indicates that a reasonable delineation of recirculating systems can be achieved in a $2 \times 2 \times 3$ matrix, based upon a system’s salinity, temperature, and trophic level. Figure 1 illustrates the classification system and assigns common names to the resulting recirculating system classes. Three eutrophic classifications (fresh/cold, cold/marine, and warm/marine) are not commonly utilized and can be dropped as categories. The resulting classifications are sufficiently different to justify unique design criteria, and should provide aquaculturists with sufficient diversity to cover most applications. The “Tropical” classification (fresh/warm/oligotrophic) warrants further refinement, as general criteria would not serve the production of the commercially important South American ornamental fish. Acidic conditions inhibit nitrification, demanding adjustments in biofiltration design rationale. Thus, a “Tropical Rain Forest” (acidic) and a “Tropical Display and Breeding” (neutral to basic) category were established. This adjustment illustrates the potential for further expansion and refinement of the classification system as recirculating industries become more sophisticated.

Table 2 illustrates relationships between the 10 classes of recirculating systems and the specific applications. A given species may appear under more than one classification based upon the system’s proposed function (broodstock conditioning, spawning, fry production, fingerling headstart, or growout). Thus, redfish/red drum (*Sciaenops ocellatus*) broodstock may be conditioned under “Marine Reef,” but fingerlings may be reared under “Marine Growout” (warm/mesotrophic). Also, based upon the production philosophy of the aquaculturist, tilapia may be grown in systems following “Warmwater Growout” (fresh/mesotrophic), or “Hardy Warmwater Growout” (fresh/eutrophic), or, given their tolerance for salinity, “Marine Growout” (warm/mesotrophic) guidelines. Ultimately, the authors trust that commercial experience will identify classifications that prove most reliable and cost-effective, allowing production associations to make firm recommendations to their members.

The classification system does not preclude further refinements in recommendations. Additional treatment requirements that are not inherently covered in the basic water quality guidelines can be appended to the basic classification. The specification for oyster depuration, for example, may be presented as “Marine Growout with Disinfection.” Or, cephalopods may demand “Marine Reef with Denitrification” (Whitson et al. 1993). The variations will stem from a commonly accepted base, however, and adoption of such refinements for a particular application
would ultimately require justification. Widespread acceptance (particularly across species) of a modifier would eventually justify the modification of the water quality specifications for a trophic level or the definition of a new category (as in the case of the "Tropical Breeding" category).

It is hoped that future modifications to the classification system can be minimized through an extended review and input period. To this end, the basic classification system has been posted in the Internet at <http://la-sea-grant.lsu.edu/recirculatingsystems/Recirqua/RecirquaDefault.htm>. Review comments are being solicited until Spring 1998. At the end of the review period, it is anticipated that a finalized classification will be published, and endorsements by the appropriate societies and associations will be sought.

Figure 1. The proposed classification system attempts to identify distinct system categories based on salinity, temperature, and trophic level.
Table 2: The existence of the recirculating classification system permits engineers to develop integrated design guidelines, and, independently, production associations can make clear recommendations as to appropriate categories for production activities by their membership.

<table>
<thead>
<tr>
<th>Class No.</th>
<th>Classification</th>
<th>Representative Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tropical Rain Forest</td>
<td>South American Discus</td>
</tr>
<tr>
<td>2</td>
<td>Tropical Display and Breeding</td>
<td>Home Aquaria</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Display Aquaria</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hybrid Bass Broodstock</td>
</tr>
<tr>
<td>3</td>
<td>Warmwater Growout</td>
<td>Tropical Ornamentals</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tilapia</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Channel Catfish</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hybrid Striped Bass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ornamental Koi Growout</td>
</tr>
<tr>
<td>4</td>
<td>Hardy Warmwater Growout</td>
<td>Carp</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tilapia</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Eels</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Alligator</td>
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<tr>
<td></td>
<td></td>
<td>Turtle</td>
</tr>
<tr>
<td>5</td>
<td>Salmonid Spawning</td>
<td>Trout broodstock</td>
</tr>
<tr>
<td>6</td>
<td>Coldwater Growout</td>
<td>Trout</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Salmon</td>
</tr>
<tr>
<td>7</td>
<td>Marine Reef</td>
<td>Soft Crab Shedding Systems</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shrimp Maturation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Redfish Broodstock</td>
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<tr>
<td>8</td>
<td>Marine Growout</td>
<td>Redfish</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Southern Flounder</td>
</tr>
<tr>
<td>9</td>
<td>Coldwater Marine Aquaria</td>
<td>Salmon Broodstock</td>
</tr>
<tr>
<td>10</td>
<td>Coldwater Marine Growout</td>
<td>Salmon</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lobster</td>
</tr>
</tbody>
</table>

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References


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