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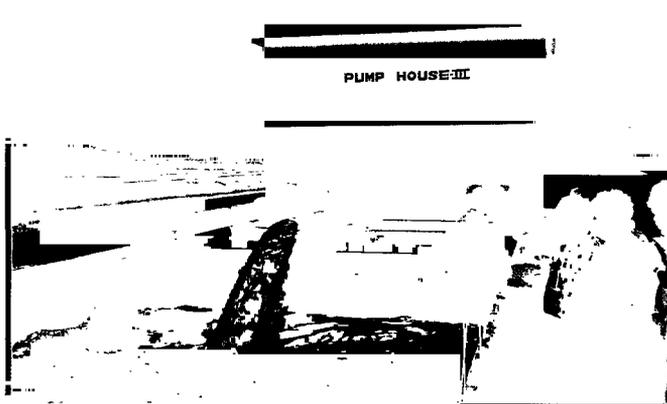
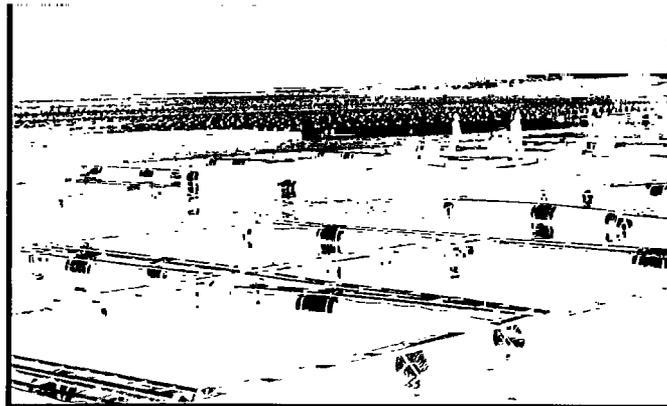
Rural Development

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Source Water Quality for Aquaculture

A Guide for Assessment



*Ronald D. Zweig
John D. Morton
Macol M. Stewart*

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A Guide for Assessment

*Ronald D. Zweig
John D. Morton
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*The World Bank
Washington, D.C.*

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Photographs by Ronald Zweig. Clockwise from top right: (1) Marine fish culture in floating cages surrounded by shellfish and seaweed culture (suspended from buoys in background), which feeds on released fish wastes. Sea cucumbers stocked beneath the cages feed on the settled fish wastes. Weihai Municipality, Shandong Province, China. (2) Pump house brings water from Bay of Bengal to Banapada Shrimp Farm, Orissa, India. (3) Day-old carp hatchlings are released to a nursery cage in a fish hatchery pond prior to sale to stock fish production farms. Yixing, Jiangsu Province, China.

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Contents

Foreword	v
Abstract	vii
Acknowledgments	viii
Abbreviations and Acronyms	ix
Glossary	x
Chapter 1 Assessing Source Water Quality	1
Choice of Source Water	1
Source Water Quality Issues	1
Guidelines for Evaluating Source Water Quality	3
Chapter 2 Phase I: Physio-chemical Water Quality Parameters	6
Basic Factors	6
Other Critical Factors	18
Chapter 3 Phase II: Anthropogenic and Biological Water Quality Parameters	22
Metals	22
Metalloids	31
Organic Compounds	33
Pathogens and Biological Contaminants	39
Chapter 4 Phase III: Field Study	42
Study Design	42
Criteria for Fish Growth and Health	42
Criteria for Contaminant Residues	43
Appendix Tables	44
Notes	53
Bibliography and Related Sources	55
Species Index	61

Boxes

- 1.1 Bioaccumulation 5
- 3.1 Protecting aquaculture ponds from pesticides 37

Figure

- 1.1 Analytical process for evaluating source water quality for aquaculture 4

Tables

- 1.1 Advantages and disadvantages of common water sources 2
- 2.1 General temperature guidelines 6
- 2.2 Optimal rearing temperatures for selected species 7
- 2.3 Turbidity tolerance levels for aquaculture 8
- 2.4 Optimal salinities for selected species and general guidelines 9
- 2.5 Alkalinity tolerance levels for aquaculture 10
- 2.6 pH tolerance levels and effect for aquaculture 11
- 2.7 Hardness tolerance levels for aquaculture 11
- 2.8 Optimal ranges for total hardness 12
- 2.9 Recommended levels of dissolved oxygen for aquaculture 13
- 2.10 Carbon dioxide tolerance levels for aquaculture 15
- 2.11 Factors affecting the toxicity of ammonia to fish 16
- 2.12 Ammonia tolerances for aquaculture 17
- 2.13 Optimal nitrite concentrations for aquaculture 18
- 2.14 Optimal nitrate concentrations for aquaculture 18
- 2.15 Optimal mud characteristics for aquaculture 20
- 3.1 Maximum cadmium concentrations for aquaculture 26
- 3.2 Maximum lead concentrations for aquaculture 27
- 3.3 Maximum copper concentrations for production of salmonid fish 28
- 3.4 Maximum chromium concentrations for aquaculture 29
- 3.5 Maximum zinc concentrations for aquaculture recommended by the European Union 31
- 3.6 Persistence of pesticides 35
- 3.7 Toxicity to aquatic life of selected chlorinated hydrocarbon insecticides 35
- 3.8 Pesticide solubility & experimentally derived bioaccumulation factors in fish 36

Appendix Tables

- 1 Effect of biological processes on alkalinity 44
- 2 Relative abundance categories of soil chemical variables in brackish water ponds 45
- 3 Relative abundance categories of soil chemical variables in freshwater ponds 46
- 4 Selected biomarkers proposed in study of environmental and/or toxicological responses in fish 47
- 5 Provisional tolerable weekly intake for selected elements 48
- 6 Import standards for contaminant residues in fish and shellfish 49
- 7 Import bacteriological standards for fish and shellfish 51

Foreword

The United Nations Food and Agriculture Organization (FAO) reports that most species subject to capture fishing are overexploited and that the potential for increasing yields in the long term is extremely limited. Aquaculture is an attractive alternative to capture fisheries due to its potential for production expansion, effective use of processing facilities, and adaptability of production-to-market requirements. Facing the leveling of production of capture fisheries, aquaculture, has grown in production at an average annual rate of over 11 percent during 1990–94 according to FAO-reported trends. With this growth the World Bank has become increasingly involved in assisting and financing aquaculture project requests from member governments. This report is thus meant to help private and public sectors and lending institutions determine whether the water quality at a proposed aquaculture development site is acceptable. The need for such a guide has become important and necessary with the continued degradation of water resources from increases in industrial and municipal wastewater discharges and agro-chemical use.

Water is the most important input for aquaculture and thus a key element in the success of these projects. Source water should be selected based on its suitability for efficient production of high-quality aquaculture product(s). Poor water quality may impair the de-

velopment and growth of fish and shellfish. It may also degrade the quality of the product by tainting the flavor or by causing accumulation of high enough concentrations of toxic substances to endanger human health. The importance of water quality along with the growth of the World Bank's involvement in aquaculture projects has created a need of a guide for determining the suitability of source waters proposed for use in these projects. It is the goal of this report to provide information useful to this end.

This report reviews the quality standards for water and fish product, looks at the parameters of greatest importance to aquaculture, and discusses the scientific basis for these standards. It can provide government officials, field technicians, and task managers with necessary information to make informed judgments. The report also contains practical, step-by-step guidelines for use by task managers in determining whether the quality of the proposed source water will present a significant risk to the success of a project. The prescribed procedures would be of importance to site selection for any considered aquaculture enterprise and would also be of use to governments involved in formulating inland and coastal zone development/management plans that would include assessment of appropriate areas for the establishment of aquaculture facilities.

The information provided here is limited to that currently available in the literature and from government standards and thus is not exhaustive with regard to all species cultured and all aquacultural production systems in use.

There are plans to revise this report about every two years to keep it current with the new information being generated on the topic and also to make it available electronically on the World Bank's website (www.worldbank.org).

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Abstract

The report provides guidance on how to assess the suitability of source water for aquaculture. Aquaculture development worldwide is growing rapidly due to increasing demands for its products and limited production potential from inland and marine capture fisheries. The report reviews the different sources of water that are or can be used for aquaculture and provides the current standards on acceptable physio-chemical, anthropogenic pollutant, and biological factors that affect the quality of source water. It provides the available knowledge from a literature review on these factors and the potential impact on the health of various cultured

organisms (mostly finfish and crustaceans) and upon the consumer due to the presence and/or bioaccumulation of toxins and pathogens that can be present in water. The current state of knowledge on the acceptable limits of hazardous chemicals and pathogens in water used for fisheries and aquaculture and the acceptable concentrations accumulated in the tissue of aquaculture products are also furnished. These standards vary somewhat among countries. The report also suggests a step-by-step process for evaluating source water quality for aquaculture that minimizes cost to the degree possible.

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Abbreviations and Acronyms

Ag	Silver	HOCl	Hypochlorous acid
Al	Aluminum	KMnO ₄	Potassium permanganate
As	Arsenic	LC ₅₀	Lethal count level (50 years)
ASP	Amnesiac shellfish poisoning	mg l ⁻¹	Milligrams per liter
BCF	Bioconcentration factors	Mn	Manganese
BOD	Biological oxygen demand	MPN	Most probable number
CaCO ₃	Calcium carbonate	N ₂	Nitrogen gas
Cd	Cadmium	Ni	Nickel
CFU	Colony forming units	NSP	Neurotoxic shellfish poisoning
Cl	Chlorine	Pb	Lead
CN	Cyanide	PCB	Polychlorinated biphenyls
COD	Chemical oxygen demand	ppb	Parts per billion
CO ₂	Carbon dioxide	PSP	Paralytic shellfish poisoning
Cr	Chromium	PTWI	Provisional tolerable weekly intake
Cu	Copper	Se	Selenium
DO	Dissolved oxygen	Sn	Tin
DSP	Diarrhetic shellfish poisoning	TAN	Total ammonia nitrogen
DDT	Dichloro-diphenyl-trichloro-ethane	TBT	Tributyl tin
EU	European Union	TCDD	Tetrachloro dioxin
FAO	United Nations Food and Agriculture Organization	TGP	Total gas pressure
Fe	Iron	USEPA	United States Environmental Protection Agency
HCN	Hydrogen cyanide	WHO	World Health Organization
H ₂ S	Hydrogen sulfide	Zn	Zinc
Hg	Mercury	‰	Parts per thousand

Glossary

Actinomycetes: Any of an order (Actinomycetales) of filamentous or rod-shaped bacteria, including the actinomyces (soil-inhabiting saprophytes and disease-producing parasites) and streptomycetes.

Anthropogenic pollutants: Pollutants which come from human sources such as emissions from an industrial plant or pesticide emissions from agriculture. These pollutants are referred to as anthropogenic because they typically are associated with human activity. However, it is possible for some of them to come from natural sources.

Benthos: organisms that live on or in the bottom of bodies of water.

Bioaccumulation factor (BCF): A measure of the extent to which a compound bioaccumulates in an aquatic species. It is calculated as (concentration of the compound in the body tissue) divided by (concentration of the compound in the water).

Biological oxygen demand (BOD): The amount of dissolved oxygen used up by microorganisms in the biochemical oxidation of organic matter. Five-day BOD (BOD₅) is the amount of dissolved oxygen consumed by microorganisms in the biochemical oxidation of organic matter over a 5-day period at 20°C.

Cations: The ion in an electrolyzed solution that migrates to the cathode: a positively charged ion.

Chelating Agents: A compound that combines with a metal.

Chloracne: An eruption/inflammation of the skin resulting from exposure to chlorine.

Colony forming units: A measure of bacterial numbers which is determined by growing the bacteria and counting the resulting colonies.

Detritus: loose material (as rock fragments or organic particles) that results directly from disintegration.

Divalent: Having a valence (combining power at atomic level) of two [e.g., Calcium (Ca²⁺)].

Hypoxia: Acute oxygen deficiency to tissues.

Ligands: A group, ion, or molecule coordinated to a central atom or molecule at a complex.

Most probable number: A measure of bacterial numbers in which the bacteria are serially diluted and grown. By identifying the dilution samples in which the bacteria grow, the number of bacteria in the original samples can be determined.

Necrosis: Localized death of living tissue.

Osmoregulation: The biological process of maintaining the proper salt concentration in body tissues to support life.

Parenchymatous: related to the essential and distinctive tissue of an organ or an abnormal growth as distinguished from its supportive framework.

Physio-chemical properties of water: The basic physical and chemical properties of water including salinity, pH etc. Note this does not include concentrations of anthropogenic pollutants.

Redox: Of or relating to oxidation-reduction.

Tainting or Off-flavor: When certain pollutants such as petroleum hydrocarbons accumulate in fish or shellfish to a level at which the flavor is affected. This makes the product undesirable for human consumption.

Zeolites: Any of various hydrous silicates that are analogous in composition to the feldspars, occur as secondary minerals in cavities of lavas, and can act as ion exchangers used for water softening and as absorbents, and catalysts.

Assessing Source Water Quality

Water is the most important element for aquaculture. Selection of source water should be based on its suitability for efficient production of a high quality aquaculture product. Poor water quality may affect fish and shellfish health through impairment of development and growth or may degrade the quality of the product by tainting its flavor or by causing accumulation of high concentrations of toxic substances which could endanger human health. The importance of water quality has created a need for guidelines for determining the suitability of source waters proposed for use in these projects.

Choice of Source Water

The first step is identification of the most promising source water by carefully considering the advantages and disadvantages of different types of water sources. Water sources fall into roughly nine categories: marine/coastal, estuaries, rivers/streams, lakes, surface runoff, springs, wells, wastewater, and municipal water.

In general, for fresh water aquaculture, groundwater sources (springs and wells) are preferred. They maintain a constant temperature, are free of biological nuisances such as fish eggs, parasites and larvae of predatory insects and are usually less contaminated than surface water sources. Ground water has traditionally been less contaminated than surface water. Contamination of ground water sources

has become common in industrialized nations, a trend threatening the industrializing countries of Asia.

For aquaculture in salt or brackish water, preference is for source water that is away from any generator of pollution, such as industries, tainted river mouths, or agricultural areas. This water is less susceptible to fluctuations in salinity and other chemical properties and is less likely to be contaminated by coastal discharges (Lawson 1995, 52). The most common advantages and disadvantages of each type of source are shown in table 1.1.

Source Water Quality Issues

Once potential source waters are identified, it is imperative to insure the water quality is suitable for aquaculture. Poor water quality may cause project failure by producing a product either in insufficient quantity or unmarketable size or quality. Water quality can cause death, disease, or poor growth in fish and shellfish. In addition, poor water quality can contaminate the product with compounds dangerous to human health.

Fish and Shellfish Health

Fish and shellfish health is very sensitive to water quality. Water quality criteria are based on studies of growth, behavior, and health of different species in various waters. One set of parameters which affect fish and shellfish are

Table 1.1 Advantages and disadvantages of common water sources

<i>Source</i>	<i>Advantage</i>	<i>Disadvantage</i>
Marine/coastal	Constant temperature High alkalinity	May contain contaminants May require pumping
Estuarine	May be readily available Inexpensive	May contain contaminants May be subject to large fluctuations in temperature
River/stream	May be readily available Inexpensive Pumping costs lower than wells	Typically requires pumping Often have high silt loads Can contain biological nuisances such as parasites and larvae of predatory insects May contain contaminants May contain excessive nutrient concentrations Have seasonal and possibly diurnal fluctuations in flow, temperature, and chemistry
Lake	May be readily available Inexpensive Pumping costs lower than wells	Similar to river/stream, but chemistry is more stable due to the buffering effect of the large water volume Bottom water may be anoxic in summer and contain reduced iron
Surface runoff	Inexpensive	May contain contaminants Unreliable Requires 5-7 acres of watershed per surface acre of aquaculture water
Spring	Constant temperature May not require pumps Usually less polluted (see note) Free of biological nuisances such as parasites and larvae of predatory insects Inexpensive	Typically lacking oxygen and thus needs aeration Yield and reliability may be questionable May contain dissolved gases May contain high iron concentrations or reduced iron May contain high hardness
Well	Constant temperature Usually less polluted (see note)	Typically lacking oxygen and thus needs aeration Unless artesian, requires pumps which can be costly May contain dissolved gases May contain high iron concentrations or reduced iron Possible aquifer depletion
Municipal	High quality	Expensive Typically have disinfecting chemicals which are poisonous to fish and expensive to remove
Wastewater	Inexpensive	Medium to high pathogen concentrations May contain contaminants

Note: Although ground water has traditionally been less contaminated than surface water, contamination of ground water sources has become common in industrialized nations. A similar trend may be likely for newly industrializing countries of Asia.

Source: Swann 1993 and Lawson 1995.

the basic characteristics of natural water otherwise referred to as its physio-chemical properties. These include properties such as turbidity, pH, and dissolved oxygen. For many of these properties, fish have a limited range in which they can grow optimally. Hence, screening the source water in respect to its physio-chemical properties is an important initial step in assessing the source-water suitability to fish health.

Fish health can also be affected by pollutants typical of anthropogenic (as a result of human activity) discharges such as petroleum hydrocarbons, metals and pesticides. It is possible for these discharges to also come from natural causes. These pollutants can cause deleterious behavioral and reproductive changes in fish and shellfish even at very low concentrations. To ensure good fish and shellfish health, source

water must also be screened using water quality criteria for these chemicals.

Product Quality and Human Health

The quality of the aquaculture product and its suitability for human consumption may also be affected by water quality. Even if culture species are able to grow and thrive in a given source water, low levels of pollutants may cause the aquaculture products to be contaminated or have off-flavor. Off-flavor or tainting occurs when certain pollutants such as petroleum hydrocarbons or metals accumulate in fish or shellfish to a level at which the flavor is affected, making the product undesirable for human consumption.

The process by which pollutants concentrate in seafood is called bioaccumulation (box 1.1, p. 6). Many pollutants, especially those which are fat soluble, collect in the tissues of aquatic animals. This process results in higher concentrations of pollutants in body tissues of aquatic organisms than in the surrounding water.

Accumulation of contaminants in fish and shellfish is of great concern to the aquaculture industry. Consumers are highly sensitive to the quality of food products and any potential health risks. Media reports of contamination of seafood can seriously affect consumer perception, marketing, and production of all kinds of fisheries products. In addition, rejection of aquaculture products which fail to meet import quality standards may have serious long-term implications for the exporting country and producers.

Quality standards established by national governments are the means by which humans are protected from contaminated seafood. International and domestic commerce is regulated to prevent contaminated fish and shellfish from reaching the market. Thus meeting these standards are an important goal for the products of a successful aquaculture project from both an economic and public health perspective. Such water quality standards can be incorporated into a water quality assessment. In cases where bioaccumulation is sus-

pected, tests can be done by preparing a pilot study in which fish are grown in the source water and subsequently tested for contaminant concentrations in body tissue.

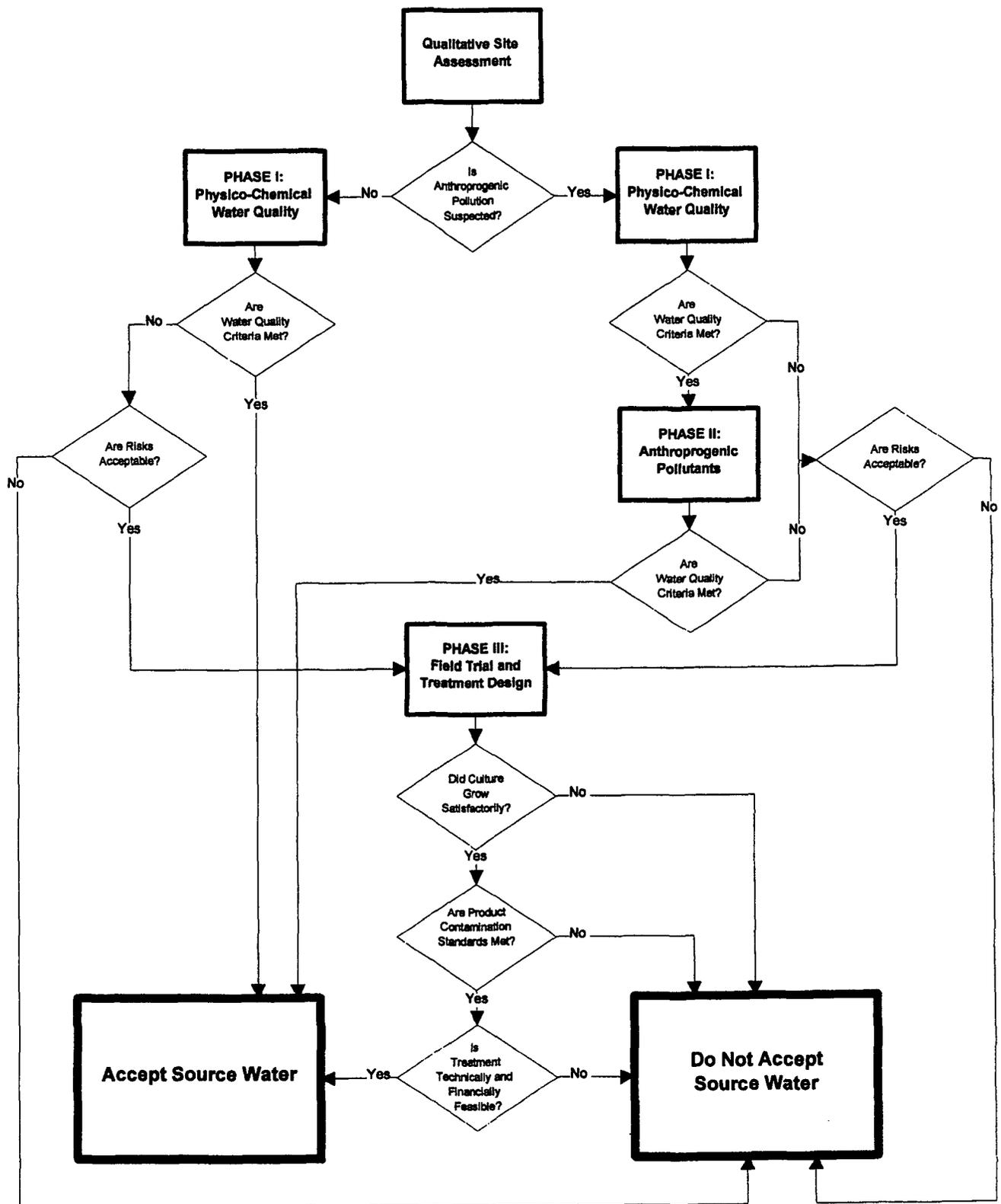
Guidelines for Evaluating Source Water Quality

In evaluating the suitability of the quality of source water for new, improved, or expanded aquaculture developments, a three-phased screening process is recommended. For water quality analysis it is recommended that those methods defined in Standard Methods for Examination of Water and Wastewater (APHA 1995) be followed which for many factors would require an expert water quality analysis laboratory to do the assays. It is also important to note that the water quality suitable for hatchery, nursery, and grow-out systems for a particular species vary to some degree and are discussed in the text with the information available for each type.

For Phase I as illustrated in figure 1.1, the water quality criteria for the basic physiochemical properties necessary to sustain the cultured organisms will be compared to measurements made on the source water. This will provide a simple means of screening the source water without going through the more expensive tests for anthropogenic pollutants. Accordingly, if anthropomorphic pollution or naturally occurring toxins (for example, arsenic, toxic algae) are not suspected and Phase I criteria are met, the source water can be considered acceptable. If Phase I criteria are not met in this circumstance, a Phase III field trial can be pursued. If the Phase III trial cannot be conducted, the water should either be rejected or accepted if a technically feasible and cost effective water treatment is identified and tested, bringing the source water within acceptable Phase I criteria.

Phase II is designed to screen for criteria on anthropogenic pollutants in source water and would be conducted after the source water has been tested and met the Phase I criteria. In addition, biological contaminants such as algal

Figure 1.1 Analytical process for evaluating source water quality for aquaculture



Box 1.1 Bioaccumulation

Bioaccumulation is a process in which chemical pollutants that enter into the body of an organism (by adsorption through the gills and intestine or by direct exposure through the skin) are not excreted, but rather collect in its tissues.

Rates of bioaccumulation in aquatic species vary greatly depending on species behavior and physiology. For example, bottom feeders are more sensitive to pollutants associated with sediments. The differences in the mechanism of regulating salt concentration between fresh and salt water fish may affect exposure to water soluble contaminants. Different species may also accumulate various pollutants in different tissues, such as muscle, kidneys, or liver. The toxicity of contaminants, bioavailability, and rates of bioaccumulation are also influenced by environmental factors such as temperature, dissolved oxygen, alkalinity, pH, redox potential, colloids, dissolved organics and suspended solids.

Species higher in the food chain tend to accumulate higher concentrations of many pollutants because they are feeding on organisms which have

pollutants concentrated in their tissues. There is little evidence that chemicals which bioaccumulate in the fatty tissues of aquatic species high in the food chain cause deleterious effects on these organisms. However, it is thought that birds and mammals which feed on these aquatic organisms experience deleterious effects. Therefore, there are considerable health concerns (for example, cancer, damage to the nervous system) about the accumulation of such substances in the tissues of fish which are consumed by humans. The U.S. Environmental Protection Agency conducted a national study of accumulated toxins in fish caught in open waters which documents the concern (USEPA 1992).

Sometimes pollutants can be naturally cleansed from the tissue of aquatic animals by placing them in clean water for a given period of time. The rate of cleansing, or depuration, depends upon the species and the contaminant in question. The only other way to address the problem of bioaccumulation is to reduce exposure of the fish to the contaminant through improved water quality.

toxins can also be screened. Because it is neither feasible nor desirable to test for every possible pollutant, only pollutants typical of current and historical industrial, municipal, and agricultural activities in the watershed should be tested. In some cases high concentrations may occur in nature. This is common in areas with large deposits of a particular mineral. If large natural sources are suspected in the area, tests should be conducted to analyze for the toxin(s). If the source water fails to meet Phase II criteria, the feasibility of pre-treating the water before use could be considered as in Phase I. A decision as to whether to pursue a Phase III field trial or reject the source water can then be made. If both Phase I and Phase II

criteria are met, it is not mandatory to pursue Phase III. However it is advised that Phase III be pursued, if possible, as a means of minimizing the risk of project failure.

Phase III involves a pilot study or field test in which fish are grown in the selected source water, using similar management techniques as those of the proposed project, and then tested for bioaccumulated pollutants and off-flavor. The pilot study could also be replaced by sampling fish and shellfish tissues from an existing aquaculture facility, if available, in the vicinity that uses the same planned technology and the source water in question. Following Phase III where implemented, a final decision can be made on the use of the source water.

CHAPTER 2

Phase I: Physio-chemical Water Quality Parameters

Basic Factors

Temperature, turbidity, salinity, alkalinity, acidity, hardness, dissolved oxygen, carbon dioxide, total gas pressure, nitrogen compounds, iron, hydrogen sulfide, methane, and water-soil interactions are the basic physio-chemical properties tested in Phase I. Because these physio-chemical properties of natural waters affect the growth and health of fish and shellfish, these parameters must be tested for in all potential water sources.

Temperature

Effects. Water temperature affects a multitude of important processes in aquaculture. Physiological processes in fish such as respiration rates, feeding, metabolism, growth, behavior, reproduction and rates of detoxification and bioaccumulation are affected by temperature. Temperature can also affect processes important to the dissolved oxygen level in water such as the solubility of oxygen, and the rate of oxidation of organic matter. In addition the solubility of fertilizers can be affected by temperature.

Guidelines. Each species has an optimum temperature at which its growth rate and heartiness are best. Growth will still occur at very close to the upper and lower lethal tem-

perature limits; however, suboptimal temperature conditions cause stress which affects behavior, feeding, metabolism, growth, and immunity to disease. It is therefore preferable that water remain near optimum temperature, and imperative that it never deviate beyond lethal limits.

Listed in table 2.1 are general guidelines and in table 2.2 species specific guidelines for source water temperature. The guidelines are based on the conditions at which optimal growth rates occur.

Treatment. Since controlling the temperature of ponds in large-scale aquaculture facilities is often not practical, sites should be selected in geographic regions which provide an ambient temperature conducive to the growth of

Table 2.1 General temperature guidelines

<i>Species</i>	<i>Temperature/comment</i>
Tropical	29–30°C / optimal growth < 26–28°C / low growth rates < 10–15°C / lethal limit
Warm-water	20–28°C / optimal growth < 0°C / lethal limit
Cool-water	15–20°C / optimal growth
Cold-water	< 15°C / optimal growth > 25°C / lethal limit

Source: Boyd 1990 and Lawson 1995.

Table 2.2 Optimal rearing temperatures for selected species

Species	Temperature (°C)	Reference
Brook trout	7–13	Piper <i>et al.</i> 1992
Brown trout	12–14	Petit 1990
Brown trout	9–16	Piper <i>et al.</i> 1982
Rainbow trout	14–15	Petit 1990
Rainbow trout	10–16	Piper <i>et al.</i> 1982
Atlantic salmon	15	Petit 1990
Chinook salmon	10–14	Piper <i>et al.</i> 1982
Coho salmon	9–14	Piper <i>et al.</i> 1982
Sockeye salmon	15	Petit 1990
Sole	15	Petit 1990
Turbot	19	Petit 1990
Plaice	15	Petit 1990
European eel	22–26	Petit 1990
Japanese eel	24–28	Petit 1990
Common carp	25–30	Petit 1990
Mullet	28	Petit 1990
<i>Tilapia</i>	28–30	Petit 1990
Channel catfish	27–29	Tucker and Robinson 1990
Channel catfish	21–29	Piper <i>et al.</i> 1982
Channel catfish hatcheries	78–82°F	Boyd 1990
Striped bass	13–23	Piper <i>et al.</i> 1982
Red swamp crawfish	18–22	Romaire 1985
<i>P. vannamei</i>	28–30	Clifford 1994
Freshwater prawn	30	Romaire 1985
Brine shrimp	20–30	Romaire 1985
Brown shrimp	22–30	Romaire 1985
Pink Shrimp	> 18	Romaire

Source: Lawson 1995.

marketable-sized products within a reasonable period of time (Lawson 1995, 14).

Turbidity

Turbidity is a measure of light penetration in water. Turbid conditions result from dissolved and suspended solids such as clay and humic compounds or microorganisms such as phytoplankton. In source water it is primarily a result of erosion during runoff. Because of the significant contribution of erosion to turbidity, caution should be used when taking source water from areas where current and future land use practices encourage erosion. Construction areas, deforested areas, and cropland have relatively high rates of erosion while for-

est and grassland have lower rates of erosion (Boyd 1996, 220–21).

In addition to turbidity from source water, turbidity may also come during the aquaculture operation. For example in the aquaculture pond turbidity can increase as a result of sediment resuspension, biological activity, the addition of manure and feed, and erosion of the pond slopes.

Effects. Turbid waters can shield food organisms as well as cause gill damage and fish stress. It can also clog filters. Turbidity levels affect the light available for photosynthesis by phytoplankton and the growth of undesirable organisms. In ponds with organisms that depend upon phytoplankton for feed, turbidity must be at sufficiently low levels to allow the penetration of light for photosynthesis. However, the turbidity must also be high enough to avoid the growth of undesirable rooted plants. The turbidity necessary for prevention of the growth of these plants can be typically provided by the phytoplankton themselves.

For ponds with organisms that derive a majority of their nutrition from feed inputs, light for phytoplankton growth is not imperative and therefore the turbidity can be higher. However, if turbidity is too high in these ponds photo-synthesis can be inhibited significantly enough to reduce oxygen levels. This can be remedied by using mechanical aeration at a rate such that oxygenation occurs without exacerbating the turbidity problem through suspension of sediment.

Because many suspended solids will settle out in ponds or canals, another major concern besides turbidity itself is the amount of suspended particles that can potentially settle out (that is, settleable solids). Sediments from highly turbid source water may fill ponds and canals within a few months. They can contain large amounts of organic matter that exerts a high oxygen demand resulting in oxygen depletion. Sedimentation can also smother eggs of some species in ponds used for natural reproduction. Sedimentation of contaminated suspended particles is also of concern in areas affected by

pollutants such as heavy metals and pesticides (Boyd 1990, 138).

Guidelines. Lethal levels of turbidity have been shown to be 500–1,000 milligrams per liter (mg l^{-1}) for cold water fish (Alabaster and Lloyd 1982). Channel catfish have tested more tolerant with their fingerlings and adults surviving long-term exposures to $100,000 \text{ mg l}^{-1}$ with behavioral changes occurring above $20,000 \text{ mg l}^{-1}$ (Tucker and Robinson 1990). Listed in table 2.3 are the ranges in which good to moderate fish production can be obtained. Recommended suspended solids concentrations for salmonid culture from different literature sources are: less than 30 mg l^{-1} , less than 80 mg l^{-1} , and less than 25 mg l^{-1} .

Treatment. Colloids or very small suspended particles can be coagulated and precipitated by adding electrolytes such as aluminum sulfate (alum). While alum is very effective, it can cause other water quality problems by reducing alkalinity and pH (see sections on pH and alkalinity). Lime can be added to counteract these effects. Turbidity caused by suspended clay can be precipitated by the addition of organics such as barnyard manure, cottonseed meal, or superphosphate. However organic matter is often difficult to obtain and apply; and it exerts an oxygen demand when decomposing. Avoiding or addressing the source of turbidity is a better strategy than chemical treatments which require frequent application and may result in other water quality problems.

Current methods of sediment (settling solids) control involve using sediment ponds or canals to remove the bulk of sediment before water enters the culture area, draining ponds and removing sediments periodically at the

end of the growing season, or dredging undrainable ponds. Sediments removed from aquaculture facilities may be considered an environmental hazard and, hence, be difficult and/or costly to dispose (Boyd 1990, 365-72).

Salinity

Salinity is a measure of the total concentration of dissolved ions in water and measured in parts per thousand (‰). Salinity varies depending on where the water source lies in the spectrum from seawater to freshwater. Typical salinity values are less than 0.5‰ for freshwater, 0.5 to 30‰ for brackish water and 30 to 40‰ for marine water.

In freshwater, the salinity and the elements contributing most significantly to salinity can vary depending on the rainfall and the geology of the area. Freshwater commonly contains relatively high concentrations of carbonate, silicic acid, calcium, magnesium and sodium (Stumm and Morgan 1981, 551).

The salinity of seawater varies depending on proximity to the coastline, rainfall, rivers, and other discharges. The elements contributing most to the salinity of seawater however do not vary markedly. Chloride and sodium ions contribute most significantly with sulfate, magnesium, calcium, potassium, and bicarbonate ions contributing to a lesser degree (Stumm and Morgan 1981, 567). Optimum salinities for selected species and general guidelines are shown in table 2.4.

Effects. Salinity is tremendously important to fish which must maintain the concentration of dissolved salts in their bodies at a fairly constant level. Through the process of osmoregulation the fish expends energy in order to maintain this level. Each organism has a range of salinity in which it can grow optimally, and when it is out of this range, excess energy needs to be expended in order to maintain the desired salt concentration. This is done at the expense of other physiological functions, if the salinity deviates too far from the optimum range.

Table 2.3 Turbidity tolerance levels for aquaculture

<i>Effect</i>	<i>Suspended solids concentration</i>
No harmful effects on fisheries	25 mg l^{-1}
Acceptable range	$25\text{--}80 \text{ mg l}^{-1}$
Detrimental to fisheries	80 mg l^{-1}

Source: Boyd 1990.

Table 2.4 Optimal salinities for selected species and general guidelines

Species	Salinity	Comment	Reference
Salmon	> 24‰	Optimum	Black 1991
Trout	< 20‰	Survival and growth decrease above 20‰	McKay and Gjerde 1985
Grass carp	< 10–14‰	Upper salinity tolerance	Maceina and Shineman 1979
<i>Tilapia aurea</i> and <i>Tilapia nilotica</i>	0–10‰	Optimum salinity	Stickney 1986
Red hybrid <i>tilapia</i>	< 17‰		Lawson 1995
Channel catfish	11–14‰ > 6–8‰ 0.5–3.0‰ < 0.5‰ < 3‰ 0.1–8.0‰	Can survive Growth is poor Optimal salinity Can still grow well Optimal for egg and fry Optimal for hatcheries	Perry and Avault 1970 Boyd 1990
Freshwater prawn <i>M. rosenbergii</i>	12.0‰ < 0.5‰	Eggs and larval stage Postlarval stages	Tansakul 1983
Brackish water prawn	15–25‰ 10–35‰	Optimum Acceptable range	
<i>P. vannamei</i>	15–25‰	Optimum	Clifford 1994
General Guidelines			
Most freshwater fish	< 0.5‰ < 2‰	Optimal Can survive at <7‰ but growth poor	Lawson 1995
Marine fish	33–34‰ 30–40‰	Optimum Acceptable range	

Treatment. Salinity may be increased by adding gypsum or sodium chloride, though costs could be prohibitive. Due to its high solubility, large increases in salinity can be obtained using sodium chloride. Generic rock salt can be used for this purpose. Gypsum is only soluble up to about 2‰ and therefore is more appropriate for affecting smaller changes in salinity (Boyd 1979). It should be noted that because increases in salinity cause particles to settle, the effect of increased sedimentation rates must be considered in any treatment to increase salinity. Lowering salinity would require advanced treatment processes such as reverse osmosis and electro dialysis, which are too expensive to be practical for most aquaculture operations.

Alkalinity

Alkalinity is a measure of the acid neutralizing capacity of a water. For the purpose of aqua-

culture, it is a convenient measure of the degree to which a water can neutralize acidic wastes and other acidic compounds and subsequently prevent extreme pH shifts, which can disturb the biological processes of the aquaculture species.² Any chemical species which can neutralize an acid can contribute to alkalinity. In natural waters, the chemical species most responsible for alkalinity are carbonate species (CO_3 , HCO_3). Hydroxides, ammonium, borates, silicates and phosphates also contribute to alkalinity.³ Total alkalinity, or the total amount of titratable bases, is expressed in mg l^{-1} of equivalent calcium carbonate (CaCO_3). Alkalinity in natural freshwater systems ranges from 5 mg l^{-1} to 500 mg l^{-1} . Sea water has a mean total alkalinity of 116 mg l^{-1} (Lawson 1995, 24).

Effects. There are no direct effects of alkalinity on fish and shellfish, however it is an important

parameter due to its indirect effects. Most importantly, alkalinity protects the organism from major changes in pH. The metabolism and respiration of fish and micro-organisms, particularly phytoplankton and bacteria, can produce wastes and by-products which can change pH. In addition some biological processes can change alkalinity itself by producing or consuming acids or bases.⁴ A summary of some processes are shown in appendix table 1.

Alkalinity may have another indirect effect on aquaculture through its effect on photosynthesis. If alkalinity is too low (less than 20 mg l⁻¹), the water may not contain sufficient carbon dioxide (CO₂) or dissolved carbonates for photosynthesis to occur, thus restricting phytoplankton growth (Lawson 1995, 24).

Guidelines. Listed in table 2.5 are the recommended general guidelines for the alkalinity of source water used in aquaculture.

pH

The pH of water is its hydrogen ion concentration ([H⁺]). It is expressed as the negative logarithm of the hydrogen ion concentration (log[H⁺]). Natural waters range between pH 5 and pH 10 while seawater is maintained near pH 8.3. The pH problems associated with aquaculture are usually not due to the source

water but to processes that occur during the aquaculture operation.⁵ However, source water with a proper pH is imperative, and the pH of any potential source water should be screened.

Effects. The pH of water used in aquaculture can affect fish health directly. For most species, a pH between 6.5 and 9 is ideal. Below pH 6.5 species experience slow growth (Lloyd 1992, 64). At lower pH, the species ability to maintain its salt balance is affected (Lloyd 1992, 87) and reproduction ceases. At approximately pH 4 or below and pH 11 or above, most species die (Lawson 1995, 26).

The pH can also indirectly affect fish and shellfish through its effects on other chemical parameters. For example, low pH reduces the amount of dissolved inorganic phosphorous and carbon dioxide available for phytoplankton photosynthesis. Also at low pH, metals toxic to fish and shellfish can be leached out of the soil. At high pH, the toxic form of ammonia becomes more prevalent. In addition phosphate, which is commonly added as a fertilizer, can rapidly precipitate at high pH (Boyd 1990, 154).

Guidelines. The effects of pH on warm water pond fish are summarized in table 2.6 along with recommended levels for salmon culture.

Treatment. Low pH waters are often treated using lime (Boyd 1981, chapter 5). Alum can be used to treat high pH waters. In cases where the high pH problem is due to excess phytoplankton photosynthesis in waters with high alkalinity and low calcium hardness, gypsum can be added as a source of calcium. Another option is to kill off phytoplankton with algaecides, but low dissolved oxygen conditions, residual adverse effects of the algicide, and high costs may result (Boyd 1990, 378).

Hardness (Calcium and Magnesium)

Total hardness is a measure of the concentration of all metal cations with the exception of

Table 2.5 Alkalinity tolerance levels for aquaculture

Total alkalinity (mg l ⁻¹)	Effect	Reference
15-20	Phytoplankton production low	Boyd 1974
< 30	Poorly buffered against rapid pH changes	Meade 1989, Tucker and Robinson 1990
20-400	Sufficient for most aquaculture purposes	Meade 1989, Tucker and Robinson 1990
≥100 or 150	Desirable	Meade 1989, Tucker and Robinson 1990

Source: Lawson 1995.

Table 2.6 pH tolerance levels and effect for aquaculture

pH levels	Effect
<i>Warm water pond fish</i>	
< 4.0	Acid death point
4.0–5.0	No reproduction
4.0–6.5	Slow growth
6.5–9.0	Desirable range for fish production
9.0–11.0	Slow growth
> 11.0	Alkaline death point
<i>Salmonid culture</i>	
6.4–8.4	Recommended range for fish production
6.7–8.6	Recommended range for fish production
6.7–7.5	Recommended range for fish production

Sources: Lawson 1995, Tarazona and Munoz 1995.

the alkali metals. Calcium and magnesium are the most common cations contributing to hardness in fresh water systems. To a much lesser extent, hardness also includes other divalent ions such as iron (Fe^{2+}) and barium (Ba^{2+}). Water is classified with respect to its hardness and softness as shown in table 2.7.

These categories were originally developed for municipal water treatment and thus have no biological relevance. It should be noted that much of the concern about hardness in water treatment is with all the ions involved, while in aquaculture the concern is mostly with the calcium concentration.

Effects. Calcium is the most important component of hardness to aquaculture. It is necessary

Table 2.7 Hardness tolerance levels for aquaculture

Water classification	Concentration (CaCO_3 per liter)
Soft	0–75 mg
Moderate	75–150 mg
Hard	150–300 mg
Very hard	> 300 mg

Source: Sawyer and McCarty 1978.

for bone and exoskeleton formation and for osoregulation. Crustaceans absorb calcium from the water when molting, and if the water is too soft their exoskeletons begin to soften and they may cease to molt. In addition, bone deformities and reduced growth rates may result if water is too soft.⁶

Hardness also affects aquaculture species and operations through its chemical interactions with other species in water. Calcium reduces the toxicity of metals, ammonia, and the hydrogen ion. In addition, due to the higher ion concentration in hard waters, suspended soil particles settle faster in hard waters than soft waters. For waters where alkalinity is high and calcium is low, photosynthesis may increase the pH to levels that are toxic to fish (Boyd 1990, 143, 377).

Guidelines. In general the most productive waters for fish culture have roughly equal magnitudes of total hardness and total alkalinity.⁷ Listed in table 2.8 are general and species specific guidelines for freshwater aquaculture. Hardness averages $6,600 \text{ mg l}^{-1}$ in ocean water and therefore is not a problem in seawater or brackish water systems (Lawson 1995, 25).

Treatment. Insufficient hardness is easily overcome. Calcium hardness can be raised by adding agricultural gypsum or calcium chloride. Gypsum is preferable because it costs less, is more readily available, and does not affect alkalinity. Its disadvantages include the variable purity of agricultural gypsum (70–98 percent) and its slow reaction rate relative to calcium chloride (Boyd 1990, 383).

Dissolved Oxygen

Dissolved oxygen (DO) is a very basic requirement for aquaculture species. It is usually the first limiting factor to occur in pond culture. Dissolved oxygen is a complex parameter because its concentration is dependent upon many processes. In an aquaculture system the sources of dissolved oxygen are photosynthesis and reaeration from the atmosphere. The

Table 2.8 Optimal ranges for total hardness

Species	Total hardness (mg l ⁻¹)	Comment	Reference
Hatchling silver carp	300–500	Optimum	Boyd 1990
Channel catfish hatchery	> 20	Optimum	Boyd 1990
Trout hatchery	10–400	Suggested	Piper <i>et al.</i> 1982
Warm water hatchery	50–400	Suggested	Piper <i>et al.</i> 1982
Freshwater crustaceans	> 50	Some species need more	Boyd 1990
Freshwater crayfish	> 100	For optimum production	De la Bretonne <i>et al.</i> 1969
General guideline	20–300	Hardness = alkalinity	Boyd and Walley 1975 Romaine 1985

sinks include oxygen-consuming processes such as respiration from microbial life, fish, and plants, and the degradation of organic matter by microorganisms (biological oxygen demand or BOD). These processes are influenced by other factors. Photosynthesis, respiration, the degradation of organic matter, and the solubility of oxygen are all influenced by temperature. The type of fish, life stage, feeding practices, level of activity and dissolved oxygen concentration also influence the respiration rate. In addition to temperature, oxygen solubility is also affected by salinity, barometric pressure and impurities. The most common cause of low dissolved oxygen in an aquaculture operation is a high concentration of biodegradable organic matter (and thus BOD) in the water. This is especially true at high temperatures. Hence BOD is possibly a more important parameter to dissolved oxygen than dissolved oxygen itself.

Effects. Dissolved oxygen concentrations near saturation levels are generally healthiest for fish. Romaine (1985) believes that growth is impaired if dissolved oxygen concentrations remain below 75 percent saturation for long periods, and Colt and Orwicz (1991) recommend that dissolved oxygen be maintained at a minimum of 95 percent saturation for optimum growth. The following generalizations were derived for warm water pond fish. For dissolved oxygen concentrations approximately 1–5 mg l⁻¹, the dissolved oxygen is still high enough for survival; however, long-term exposure results

in slow growth. As dissolved oxygen gets below 1 mg l⁻¹, it becomes first lethal after long-term exposure; and at lower dissolved oxygen, only small fish can survive short-term exposures (Lawson 1995, 23). At high oxygen concentrations, oxygen supersaturation can contribute to gas bubble trauma (see section on total gas pressure). Although when combined with other gases, oxygen can cause gas bubble trauma. High oxygen concentrations alone do not result in gas bubble trauma, but high dissolved oxygen concentrations occurring at times when water temperature increases rapidly can augment the phenomenon (Tarazona and Munoz 1995, 124). Oxygen supersaturation occurs due to high dams, aerators, and rapid photosynthesis when saturated groundwater is warmed naturally to ambient temperatures, or when saturated water is heated in hatcheries (Boyd 1990, 150–52).

Guidelines. Setting guidelines for dissolved oxygen for source water is difficult because dissolved oxygen in aquaculture operations is affected by many processes independent of the initial source-water dissolved oxygen. At the screening stage, the initial dissolved oxygen and BOD can be used to assess the ability of the source water to maintain proper oxygen levels. Other factors affecting dissolved oxygen concentration in the aquaculture operation can only be assessed and mitigated once the operation is running.

Listed in table 2.9 are the tolerances for dissolved oxygen for different species. These should be considered as a minimum for source

Table 2.9 Recommended levels of dissolved oxygen for aquaculture

<i>Species</i>	<i>DO (mg l⁻¹)</i>	<i>Comment</i>	<i>Reference</i>
<i>Tilapia</i>	> 5.0 3.0–4.0	Preferred Tolerable	Lloyd 1992
Trout	10.0 5.0	Normal at 15°C Limit for acclimation	Lloyd 1992
Marine fish	> 6.0	Minimum	Huguenin and Colt 1989
Cold water fish	> 6.0	Minimum	Lawson 1995
Salmonids	> 5.0 > 5.5 fish > 7 eggs	Can only survive lower DO for a few hours	Lloyd 1992 Roberts and Shepherd 1974
Salmon	> 8.5 100% saturation	Optimal	Black 1991
Warm water crustaceans	> 5	Can only survive lower DO for a few hours	Lloyd 1992
Eel	> 5 3.0–4.0	Preferred Tolerable	Lloyd 1992
Carp	> 5.0 3.0–4.0	Preferred Tolerable	Lloyd 1992
Fish in muddy ponds or warm, slow rivers	Resistant to low DO	Example: goldfish	Lloyd 1992
Warm water fish	> 5.0 > 1.5 > 1.0 < 0.3	More tolerant to low DO than cold water species Recommended Live for several days Live for several hours Lethal concentration	Lloyd 1992 Lawson 1995
Channel catfish	< 0.5 (fingerlings) 0.5 (adults) 2.0–3.0 < 5.0 < 6.0 (hatchery)	Survive short exposure Survive short exposure Adults survive, eggs die Feed poorly, grow slowly	Lawson 1995 Lawson 1995 Lawson 1995 Lawson 1995 Boyd 1990
Red swamp crawfish	< 1.0 (juveniles) < 2.0	Survive short exposure Adults crawl out	Avault <i>et al.</i> 1974 Lawson 1995
<i>Penaeid</i> shrimp species	low DO 0.7–1.4	Like freshwater fish Lethal concentration	Boyd 1990 Lawson 1995
<i>P. vannamei</i>	6.0–10.0	Optimum	Clifford 1994
General guideline	> 5.0–6.0		Lawson 1995

water. In addition the dissolved oxygen and BOD should be used together to assess the ability of the source water to maintain proper oxygen levels.

Treatment. Treatment of source water for low dissolved oxygen can be accomplished using

aerators. These systems typically employ mechanical mixing in order to increase the surface area of the water exposed to the air and thus the transfer of oxygen. These can take many forms including running the water over baffles or employing power aerators such as paddlewheel aerators and spray aerators.⁸

Biochemical Oxygen Demand

The biochemical oxygen demand is a measure of the amount of organic compounds that can be biologically oxidized by naturally occurring microorganisms in water.⁹ It is important in aquaculture because the degradation of organic matter by microorganisms is a major sink for dissolved oxygen, a parameter of fundamental importance to aquaculture.

Effects. As indicated earlier, the major concern of BOD is the potential for it to deplete oxygen to levels which are dangerous to fish. If a source water contains a large amount of BOD, microbial growth will be enhanced especially at high temperatures. With this microbial growth and the corresponding degradation of organic matter, oxygen will be consumed. This can lead to the depletion of oxygen in the pond and its associated effects on fish including death.

Guidelines. Like dissolved oxygen, it is difficult to establish guidelines for BOD concentrations in source water because the effects of the BOD are dependent upon many processes. BOD₅ indicates the rate of oxygen consumption in water over a 5-hour period. The optimal range of BOD₅ for cyprinid culture is recommended to be less than 8–15 mg l⁻¹.¹⁰ For wastewater-fed ponds the recommended range of BOD₅ concentrations is 10–20 mg l⁻¹ (Ghosh and others 1990, 181).

These guidelines can be used while taking into consideration factors such as the dissolved oxygen, the likely DO requirements of the culture, the degree of aeration of the pond, seasonal temperature changes, expected photosynthesis, and the oxygen solubility. A judgment can then be based on the appropriate BOD level for the source water.

Treatment. Two common options for treatment are potassium permanganate and aeration. Potassium permanganate chemically oxidizes organic matter, thus reducing the BOD. However results are often mixed and the

treatment is controversial because potassium permanganate is also an algicide; it may further decrease oxygen levels by killing algae. The lower oxygen levels are due to reduced photosynthesis and the decomposition of the dead algae.

The most effective method for reducing BOD is providing oxygen through aeration, thus accelerating the degradation of the BOD by microorganisms. The methods of aeration are similar to aeration in dissolved oxygen treatment. For rapid removal, rigorous aeration to remove BOD can be followed up by a settling basin and a sand filter to remove the microorganisms and any other particulates (Boyd 1990, 356, 386). Another method which is less costly and less efficient is to use retention ponds in which the water is held for one or two days to allow settling and oxidation of the BOD.

Carbon Dioxide

Carbon dioxide (CO₂) is a natural component of surface waters. Diffusion from the atmosphere, fish respiration, and the biological oxidation of organic compounds are the major sources of carbon dioxide in surface waters. Extraordinarily high levels of carbon dioxide are of concern in aquaculture. This can occur in source water taken from groundwaters. In addition, surface water sources can have high levels of carbon dioxide when respiration is occurring at high rates. Thus, if a source water is taken from surface waters at night or in the summer when respiration is high, there may be reason for concern.

Effects. When carbon dioxide concentrations are too high, the blood CO₂ levels of fish increase subsequently impairing the ability of their hemoglobin to carry oxygen, and causing respiratory distress (also known as the Bohr-Root effect). The severity of the Bohr-Root effect is dependent upon the oxygen level. It occurs even at high oxygen levels and becomes more severe at lower oxygen levels. A species tolerance to the Bohr-Root effect can vary. Some species are able to survive high carbon dioxide.

Table 2.10 Carbon dioxide tolerance levels for aquaculture

Aquaculture type	Free CO ₂ (mg l ⁻¹)	Comment
Hatchery	0	Ideal
Trout	< 10	
Warm water	< 15	
Channel catfish hatchery	< 10	Ideal
Finfish	< 10–15	Maximum
Trout	9–10	Toxic effects

Source: Lawson 1995, Piper and others 1982, Boyd 1990, and Petit 1990.

The channel catfish can survive CO₂ levels up to 50 mg l⁻¹ provided that sufficient oxygen is present (Tucker and Robinson 1990). Many species can tolerate high levels for short periods (Lawson 1995, 27). High carbon dioxide levels can also lower the pH, which as mentioned earlier can affect fish adversely.

Guidelines. Table 2.10 lists guidelines for carbon dioxide levels for aquaculture operations.

Treatment. Either calcium hydroxide, also known as salked or hydrated lyme, or sodium carbonate may be added to reduce high levels of carbon dioxide. Sodium carbonate is safer because, unlike calcium hydroxide, it is not caustic and will not cause a substantial rise in pH. However, calcium hydroxide is cheaper and more widely available (Boyd 1990, 379, 380). Vigorous mixing and aeration is also a good method for removing excess carbon dioxide.

Total Gas Pressure

Total gas pressure (TGP) is the sum of the partial pressures of all dissolved gases. If TGP is greater than the barometric pressure, then the water is considered supersaturated. This is of concern to aquaculture operations due to its effects on fish health. It can occur via many processes including a temperature increase, mixing waters of different temperatures, air entrainment such as in a waterfall, photosynthesis, high pressures such as those found in deep groundwater, and bacterial activity (Lawson 1995, 254).

Effects. Under supersaturated conditions, gases will come out of solution by forming bubbles, both in the water column and in the blood and tissues of aquatic animals. Fish in shallow tanks and cages are particularly susceptible because they are unable to dive to greater depths where they would be protected by higher pressure. Fish in flow-through and closed recirculating systems are also susceptible because sufficient degassing does not occur. Gas bubble trauma is rarely a problem in pond culture systems because supersaturated water added to ponds rapidly degasses (Lawson 1995, 20).

Guidelines. A total gas pressure over 105 percent saturation is considered undesirable and ideally the total gas pressure should be below 100 percent (Lawson 1995, 20). If a source water does not meet these conditions and methods are used where insufficient degassing is expected, then degassing of the source water should be considered.

Treatment. Supersaturated source water can be degassed by flowing the water through a packed column or providing vigorous agitation (Lawson 1995, 20).

Nitrogen Gas

Nitrogen gas, which is the principal gas in air, readily diffuses in and out of surface water to reach equilibrium with the atmosphere. At normal culture temperatures, water contains about 10–20 mg l⁻¹ nitrogen gas at equilibrium. Nitrogen gas is not toxic to fish or invertebrates, but supersaturation can cause gas bubble trauma.

Ammonia

Ammonia is the initial product of the decomposition of nitrogenous organic wastes and respiration, and may indicate the presence of decomposing urea, feces, and organics. High ammonia concentrations in source water are often found in groundwaters in reducing conditions such as those taken from deep wells.¹¹

Ammonia can be a larger problem for recirculating systems than for ponds because these systems do not often have phytoplankton and rooted plants to assimilate ammonia unless an adequately sized nitrifying filter is included. In pulsed flow systems such as those in irrigation ditches, high stocking densities result in high ammonia concentrations (D'Silva and Maughan 1995).

Effects. High concentrations of ammonia cause an increase in the ammonia concentration and pH in fish blood. This can cause gill damage, reduce the oxygen-carrying capacity of blood, increase the oxygen demand of tissues, damage red blood cells and the tissues that produce them, and affect osmoregulation (Lawson 1995, 32–33).

Ammonia toxicity is greatly affected by the solution chemistry. The toxicity of total ammonia nitrogen (TAN which is equal to NH_4^+ + NH_3) depends on what fraction of the total is unionized, since this is the more toxic form. Ammonium may also be toxic, but only at very high concentrations (Boyd 1990, 156). Ionized and unionized ammonia exist at an equilib-

rium depending on pH, temperature and salinity. Analytical procedures normally measure TAN, so pH, temperature, and salinity must be known to calculate the concentration of unionized ammonia.

The proportion of total ammonia nitrogen in the form of unionized ammonia increases as pH increases, so at a higher pH a smaller amount of total ammonia nitrogen causes toxic effects (Boyd 1990, 156). At lower pH TAN is less toxic because more ammonia exists as ammonium. The effect of pH on ammonia toxicity can be pronounced. A change in pH levels from 7.0 to 8.0 increases the toxicity of a given concentration of ammonia by a factor of 10 (Lloyd 1992, 37). Ammonia toxicity can be influenced by other factors such as temperature and salinity. These are summarized in table 2.11.

Guidelines. In general warm water fish are more tolerant to ammonia than cold water fish, and freshwater fish are more tolerant to ammonia than marine fish (Lawson 1995, 33). Toxic effects of unionized ammonia are usually felt at concentrations between 0.6 and 2.0 parts per

Table 2.11 Factors affecting the toxicity of ammonia to fish

Factor	Effect
Physio-chemical properties	
Temperature	Controls ratio of toxic NH_3 to NH_4^+ Increasing temperature increases ammonia toxicity
pH	Controls ratio of toxic NH_3 to NH_4^+ Increasing pH increases ammonia toxicity
DO	Low DO increases ammonia toxicity
Plants	
Photosynthesis	Increases DO Reduces carbon dioxide; increases pH of water
Respiration	Reduces DO Increases carbon dioxide; decreases pH of water
Gill Surface	
CO_2 excretion	Increased respiration increases CO_2 excretion; reduces pH of water Increased CO_2 in incoming water lessens pH reduction
Acclimation	
Environmental ammonia	May increase detoxification capability May be linked with protein content of food

Source: Lloyd 1992.

Table 2.12 Ammonia tolerances for aquaculture

Species	Ammonia (mg l ⁻¹ of NH ₃)	Comment	Reference
<i>M. rosenbergii</i>	0.09	Reduced growth rates	Boyd 1990
<i>Penaeid</i> shrimp	0.45	50% growth reduction	Boyd 1990
<i>P. monodon</i>	< 0.13	Safe concentration	Boyd 1990
<i>P. vannamei</i>	< 0.1	Optimum	Clifford 1994
Freshwater fish	0.1–1.0 mg l ⁻¹ TAN	Optimum	
	< 0.05	Safe concentration	Lawson 1995
	< 1.0 mg l ⁻¹ TAN		
Channel cat. hatchery	< 0.05	Optimum	Boyd 1990
Salmonid hatchery	< 0.0125	Upper limit	Piper <i>et al.</i> 1982
Salmonids	< 0.02		EU 1979
Marine fish	< 0.01	Safe concentration	Huguenin and Colt 1989
General guidelines	< 1.0 mg l ⁻¹ TAN	Permissible level	Meade 1989
	0.1	Max tolerable level	Pillay 1992
	< 0.012	Permissible level	Boyd 1990
	< 0.02	Permissible level	Meade 1989

million (mg l⁻¹), but some species may be less tolerant. Because there is little consensus regarding permissible levels of ammonia, it is best to be conservative. Listed in table 2.12 are species-specific ammonia tolerances to use in assessing the suitability of the source water.

Treatment. As mentioned earlier, ammonia is primarily a problem in recirculating systems where ammonia is produced at a faster rate than it is oxidized. In these cases biological filters are used (Lawson 1995, 215–47). In brackish water shrimp farms, zeolites are known to be added to control ammonia concentrations. Zeolites have been shown to be technically effective in freshwater; however recent research has put into question the efficacy and cost effectiveness of this method in salt water and brackish water systems (Briggs and Funge-Smith 1996). Other options include using aeration to oxidize the ammonia to nitrate (nitrification) or to adjust the pH and use air stripping to volatilize the ammonia.¹²

Nitrite

Nitrite is formed primarily as an intermediary in the conversion of ammonia to nitrate, a process known as nitrification (see appendix table 1).

Because it gets converted to the nitrate end-product quickly, high nitrite concentrations are not common in aquatic systems. Nitrite is not a common source water problem. More commonly, it becomes a problem during operation of recirculating systems where the water is continually reused (Lawson 1995, 35).

Effects. High nitrite concentrations deactivate hemoglobin in the blood of fish thus causing hypoxia. This condition is referred to as brown blood disease. A similar effect is found in crustaceans (Lawson 1995, 34).

Nitrite toxicity is affected by many chemical factors. Among the most important is the reduction of toxicity by ions such as calcium, chloride, bromide and bicarbonate. As a result, it is rarely a problem in saltwater and brackish water. For example, nitrite is 55 times more toxic to milkfish (*Chanos chanos*) in freshwater than in water with 16‰ salinity (Boyd 1990, 161). It has also been found that the combination of high nitrite concentrations and low chloride levels can result in reduced feeding activities, poor feed conversions, lower resistance to disease, and mortality (Lawson 1995, 34). Other evidence shows increasing pH, low dissolved oxygen and high ammonia increases the toxicity.¹³

Table 2.13 Optimal nitrite concentrations for aquaculture

Species or water	Concentration (mg l ⁻¹)	Comment	Reference
Hard freshwater	< 0.1		Pillay 1992
Soft water	< 0.1		Meade 1989
Freshwater fish	< 0.5	Hatcheries	Swann 1993
Brackish water shrimp	< 4.5		Boyd 1990
<i>P. monodon</i>	< 4.5	Postlarval growout	Boyd 1990
<i>P. vannamei</i>	< 1.0	Optimum	Clifford 1994
Salmonid	< 0.01	Soft water	Pillay 1990
	< 0.1	Hard water	

Guidelines. Listed in table 2.13 are recommended levels of nitrite in aquaculture facilities. They can be used as a guide to assess the suitability of a given source water for aquaculture.

Treatment. In recirculating systems the biological filters mentioned for ammonia removal are also used for nitrite. If treatment of source water before use is desired, aeration can be used to promote the nitrification process and conversion to nitrate.¹⁴

Nitrate

Nitrate is the least toxic of the major inorganic nitrogen compounds. It is formed as the end product of the nitrification process and concentrations are generally higher than both ammonia and nitrite.

Effects. High levels of nitrate can affect osmoregulation and oxygen transport, but toxic concentrations are much higher than for ammonia and nitrites (Lawson 1995, 35). High nitrate levels can also result in eutrophication and excessive growth of algae and aquatic plants which might have a negative impact on culture species.

Guidelines. Listed in table 2.14 are recommended nitrate levels on a species specific and general basis.

Treatment. Nitrate can be converted to nitrogen gas by the process of denitrification. It can then be removed by volatilization. These treatment systems can be difficult to run and are generally expensive.¹⁵

Other Critical Factors

Iron and Manganese

Iron (Fe) is found in two oxidation states in natural systems. Ferrous iron (Fe²⁺) is the reduced form and ferric iron (Fe³⁺) is the oxidized form. The reduced form of the metal which predominates in nonoxygenated (anoxic) waters is relatively soluble while the oxidized form which predominates in oxygenated waters is very insoluble. The difference in solubility causes problems when using source water with high concentrations of reduced iron. If a source water contains a lot of reduced iron, the iron will precipitate once the source water is oxygenated. The precipitate can then have deleterious effects upon the operation. Common sources of ferric iron are bottoms of large reservoirs during summer, and deep ground water (Boyd 1990, 165).

A very similar situation exists for manganese (Mn). The oxidized form (Mn⁴⁺) is much less soluble than the reduced form (Mn²⁺). If high concentrations of reduced manganese exist in a source water, it will oxidize and precipitate causing similar problems as iron.

Table 2.14 Optimal nitrate concentrations for aquaculture

Species	Concentration (mg l ⁻¹)	Comment	Reference
Carp	< 80	Optimum	Svobodová et al. 1993
Trout	< 20	Optimum	Svobodová et al. 1993
<i>P. vannamei</i>	0.4–0.8	Optimum	Clifford 1994
Freshwater hatchery	< 3	Optimum	Piper et al. 1982
General guidelines	< 3	Permissible	Meade 1989
	< 100		Pillay 1992

Effects. If waters which have high concentrations of reduced iron or manganese are used directly for filling aquaria or tanks for holding fish, the precipitates may occlude gills and cause stress or mortality. This is less of a problem in earthen ponds where the volume of water is greater and the iron or manganese precipitates near the inflow and does not harm fish. Channel catfish ponds can even be filled with water containing 20 to 50 mg l⁻¹ of ferrous iron, but such waters are not suitable for direct use in hatcheries (Boyd 1990, 165). In general manganese is in lower concentrations in the environment than iron and therefore is less of a concern than iron. In addition to the problems with precipitation, iron also encourages the growth of iron-metabolizing bacteria which form an orange slime that can clog pipes, filter, and other equipment (Lawson 1995, 36).

Guidelines. Iron concentrations less than 0.5 mg l⁻¹ would be appropriate for hatcheries of channel catfish and other warm water species, while the optimal iron concentration for cold water hatcheries is less than 0.15 mg l⁻¹.¹⁶ Iron concentrations of less than 0.2 mg l⁻¹ are recommended for cyprinid culture and concentrations of less than 0.1 mg l⁻¹ are recommended for marine aquaculture systems.¹⁷ But Meade (1989) conservatively recommends a general standard of less than 0.01 mg l⁻¹. A general standard for manganese concentrations in source water is less than 0.01 mg l⁻¹.

Treatment. Ferrous iron can be removed with potassium permanganate (KMnO₄), but the procedure is seldom practical because potassium permanganate is toxic to phytoplankton and expensive. Orthophosphate is adsorbed by the precipitating ferric hydroxide, so ponds must often be fertilized after treatment (Boyd 1990, 358).

The simplest method for removing reduced iron and manganese is to retain water for one or two days in a holding pond, which will allow the reduced forms (ferrous iron) to naturally oxidize to the oxidized forms (ferric iron), precipitate and settle out. If rapid removal is

necessary, water can be vigorously agitated with mechanical devices or spilled through towers, and then passed through a sand filter or settling basin. In small-scale operations, iron can be removed with filters and water softeners alone, but this method is not practical for large-scale aquaculture facilities (Lawson 1995, 38).

Hydrogen Sulfide

Hydrogen sulfide (H₂S) is produced by bacteria under oxygen starved (anoxic) conditions. It can be found in source water taken from ground water and oxygen-starved areas of surface water. It is of great concern to aquaculture as it is very toxic to fish.

Effects. Even extremely low concentrations of hydrogen sulfide cause hypoxia and are deadly or extremely harmful to fish. Concentrations as little as 0.05 mg l⁻¹ have caused death after only a brief exposure and concentrations less than 0.01 mg l⁻¹ have inhibited reproduction.¹⁸

Guidelines. While hydrogen sulfide produced by heterotrophic bacteria under anaerobic conditions inside culture facilities can be treated, any sign of hydrogen sulfide in source water is cause for alarm. Source water found to contain even the lowest levels of hydrogen sulfide is questionable as to its suitability as a source water.

Treatment. Oxidation with potassium permanganate or dilution through water exchange are the best methods of hydrogen sulfide removal. The formation of hydrogen sulfide in ponds can be prevented by vigorous aeration and circulation to eliminate anaerobic zones (Lawson 1995, 38). As a method of hydrogen sulfide removal, some companies in Asia are selling photosynthetic bacterial additives which claim to convert hydrogen sulfide to sulfate. There is no evidence that these bacterial supplements can lower concentrations of hydrogen sulfide in ponds. In fact, the commercially sold bacteria are naturally abundant in aquaculture environments and do not need to be added (Boyd 1990, 387).

Methane

Methane, also known as marsh gas, results from anaerobic decomposition in pond muds. Odorless and flammable, methane might be found in water taken from the bottom of lakes and reservoirs during summer.

Guidelines. Methane concentrations below 65 mg l⁻¹ are not harmful to fish (Boyd 1990, 163).

Water-Soil Interactions

The chemistry of natural waters is affected by the chemistry of the soil and sediment in the water. Exposing water to soils and sediments often results in chemistry which may be very different from that of the original source water. Although little is known about these interactions, they may have important consequences, either advantageous or deleterious, for the success of an aquaculture project.

Effects. From the limited studies performed, mud may have a large influence on productivity, especially in brackish water paddy culture systems, such as those in India, which use little or no input of nutrients. In pond culture of *Penaeus monodon*, the highest yields were obtained with muds containing greater than 1.0 percent organic carbon, greater than 124 mg l⁻¹ available nitrogen, and 13 mg l⁻¹ available phosphorous. Other possible water-soil interactions include ammonia release during organic decomposition, phosphorous release, increased oxygen demand, changes in redox potential and production of reduced substances, and changes in pH.¹⁹

Guidelines. Because there is not enough research on the effects of soils and sediments on aquaculture, it is difficult to subscribe definitive guidelines. Listed in table 2.15 are the results of one study that provides some recommendations. A more thorough study completed recently also provides useful information. This study sampled soils and sediments from all over the world. Although the effects on produc-

Table 2.15 Optimal mud characteristics for aquaculture

Variable and range	Potential for fish production	Optimum for <i>P. monodon</i>
<i>pH</i>		
< 5.5	Low	
5.5–6.5	Average	
6.5–7.5	High	
7.5–8.5	Average	
> 8.5	Low	
<i>Available phosphorus</i>		
< 30 mg l ⁻¹	Low	> 13 mg l ⁻¹
30–60 mg l ⁻¹	Average	
> 60 mg l ⁻¹	High	
<i>Available nitrogen</i>		
< 250 mg l ⁻¹	Low	> 124 mg l ⁻¹
250–759 mg l ⁻¹	High	
<i>Organic carbon</i>		
< 0.5%	Low	> 1.0%
0.5–1.5%	Average	
1.5–2.5%	High	
> 2.5%	Low	
<i>C/N ratio</i>		
< 5.0	Low	
5.0–10.0	Average	
10.0–15.0	High	

Sources: Banerjee and Gosh 1963, and Banerjee 1967 in Boyd 1990, and Chakraborti and others 1985.

tion were not addressed, the data (shown in appendix tables 2 and 3) provides typical soil and sediment characteristics for working aquaculture facilities throughout the world. By comparing soil characteristics in the source water and at the proposed site with these values, potential problems may be able to be red-flagged during the screening process.

Soil Acidity

Soils may be acidic and subsequently reduce the pH of the water causing deleterious effects upon the aquaculture operation. Acidic soils in aquaculture are typically due to either the existence of iron pyrite in the soil or due to a large proportion of exchangeable acidic cations (primarily aluminum ion, Al³⁺) adsorbed to the soil.

Under oxygenating conditions, iron pyrite in soils forms sulfuric acid thus causing a de-

crease in pH to typically less than 3.5.²⁰ A soil which is in this state is referred to as an acid-sulfate soil. Acid-sulfate soils typically develop in brackish water swamps that are high in iron pyrite and they also result from acid mine drainage (Boyd 1990, 182). In addition, acid-sulfate soils are particularly prevalent in ponds constructed on former mangrove swamps. Acidic soils not containing iron pyrite lower the pH of the solution as a result of exchangeable acidic cations which disassociate with the soil and react with the water as an acid.

Effects. Acid soils can reduce the pH of the water and causing the deleterious effect of low pH mentioned earlier. Acid-sulfate soil conditions also tie up nutrients (including fertilizers), thus reducing primary production and wasting fertilizer (Joseph 1990, 319).

Guidelines. Potential acid-sulfate soils may be identified as either having a sulfur concentration greater than 0.75 percent or a low pH (2–3)

upon drying for several days.²¹ For acidity in general, it has been suggested that for a soil pH of less than 6.5 and a source water with a low total alkalinity (less than 20 mg l⁻¹), treatment (using liming) will be required. In addition the pH guidelines given under water-soil interactions and the average soil pH of aquaculture operations in Appendixes 2 and 3 can provide some guidance.

Treatment. There is no feasible way of treating the soil to remove iron pyrite. However, measures can be taken to mitigate the effects. These include: draining soils and waiting until natural oxidation and leaching removes the acidity, using lime to neutralize the acidity, and prevention of the oxidation of iron pyrite so that sulfuric acid is not produced. It should be noted that the time to remove the acidity in first technique is several years and the lime requirements for the second technique are so large it is often unfeasible. Acid soils other than those caused by the presence of iron pyrite can be treated using lime.²²

Phase II: Anthropogenic and Biological Water Quality Parameters

Metals, metalloids, organic compounds, pathogens and biological contaminants are the parameters addressed in Phase II. Because testing for all of these parameters can be expensive, identification of the parameters of greatest concern will be made. This is done by determining the pollutants expected from past, present and future agricultural, industrial, and domestic activities in the area. In addition any historical evidence for algal or phytoplankton blooms in the area can be reviewed. The parameters of concern can then be tested for and compared to the guidelines presented here.

Metals

Major anthropogenic sources of metals include ore mining and processing, smelters, plating industries, tanneries and textile industries. The resulting metal pollution is of concern to aquaculture because of the potential toxic effects and the ability of many metals to bioaccumulate, thus reducing product quality and causing public health risks.

In general the effects of metals are dependent upon which form predominates of the many different aquatic chemical forms of metals. In solution metals form complexes with ligands such as hydroxide ions and carbonate ions. Stronger complexes are also formed with chelating agents such as organic matter. Metals

form complexes with particulates such as oxides, clays and particulate organic matter. Toxicity is usually related to the dissolved, uncomplexed forms of the metals, rather than to the adsorbed, chelated, or complexed forms which are more common. In addition to its reduction through binding to particulates and complexing ligands, the concentration of the toxic dissolved, uncomplexed forms are reduced at high pH. Toxicity of metals are also reduced at high salinity due to competition of ions with the metals.²³ Therefore metals are less likely to be a problem in marine aquaculture systems than in freshwater systems. Some metals bioaccumulate in fish and shellfish thus causing a potential threat to public health.

The following sections summarize the sources, environmental behavior, background levels, and toxicities of the metals. In addition, guidelines to assess the source water are also presented. It should be noted that although this document treats contaminants in isolation, they are likely to occur in concert with other contaminants and water quality problems. A mixture of metals at concentrations below their individual toxicity thresholds may produce toxic effects through their joint action (Furness and Rainbow 1990, 116). The following section reflects the bias in the literature towards the focus on criteria for contaminant concentrations in the water column, but concentrations in sediments may be as important, if not more

so. In some instances sediments may be the most appropriate measure of contamination, yet few standards exist for sediment contamination.

Mercury

Mercury (Hg) naturally occurs in the environment as a result of the volcanic degassing of the Earth's crust and weathering of mercury-rich geology. While water from areas rich in mercury ores may exhibit high local mercury concentrations, industrial processes, agriculture, and the combustion of fossil fuel are the most significant sources of aquatic contamination. Common sources include caustic soda, pulp and paper, and paint manufacturing. Mercury is also used in batteries, dental amalgam, and in bactericides.

Environmental behavior. Mercury occurs in both inorganic and organic forms in water. Its most predominant forms in freshwater are hydroxide complexes and in saltwater as a chloride complex (Stumm and Morgan 1981, 372). Mercury also exists as the mercuric ion (Hg^{2+}) and under anoxic conditions, as the neutral, reduced form (Hg^0). In soils it can precipitate out as stable mercuric sulphide (Dojlido and Best 1993, 92). Methyl mercury is formed by bacteria from mercuric ions under both aerobic and anaerobic conditions. It is this form that bioaccumulates in fish and shellfish.

Background levels. Mercury levels in water are much lower than levels in sediments. Natural background concentrations average 0.1 mg l^{-1} dry weight in soils, and 0.19 mg l^{-1} dry weight in sediments.²⁴ Background levels for unpolluted waters fall in the range of 0.001 to 0.003 parts per billion (ppb) for lakes and rivers, 0.002 to 0.015 ppb for coastal waters, and 0.0005 to 0.003 ppb for the open ocean.

Effects on fish health. The lethal levels of mercury for fish range from 1 mg l^{-1} for tilapia to 30 mg l^{-1} for guppies and 2 mg l^{-1} for a crustacean (*Cyclops abyssorum*).²⁵

Effects on bioaccumulation. While methyl mercury accounts for more than 90 percent of the mercury found in fish at higher trophic levels, it constitutes less than 1 percent of the total mercury found in aquatic systems (Malm and others 1990, 12). Methyl mercury is 1,000 times more soluble in fats than in water and concentrates in muscle tissue, brain tissue, and the central nervous system. Hence mercury levels in fish may be in excess of 10,000 to 100,000 times the original concentration in surrounding waters. The contaminant rises through the food chain and high concentrations of mercury accumulate in predators such as trout, pike, walleye, bass, tuna, swordfish, and shark. In highly contaminated areas methyl mercury may be accumulated in smaller species which are lower in the food chain such as those found in aquaculture (Philips 1993, 302). In addition to fish, aquatic invertebrates also accumulate mercury to high concentrations.²⁶

Accumulation is fast while depuration is slow. Slightly contaminated shrimp are slow to depurate mercury, while contaminated oysters depurate rapidly. Unlike oysters, shrimp consume sediment-dwelling organisms which may contain a higher proportion of methyl mercury than plankton and detritus in the water column. Mercury depuration in fish is also extremely slow. The half-life of methyl mercury in fish is estimated at two years (Palmer and Presley 1993, 566).

Levels of methyl mercury in fish have also been correlated with the age and size of the fish, the species, pH of the water, and mercury content of water and sediments (WHO 1989b, 33). However the processes affecting mercury behavior in the environment are too complex for prediction with the current state of knowledge.

Effects on human health. The general population does not face a significant health risk from mercury. Exposure is primarily through diet. In most foodstuffs mercury is largely in the inorganic form and at very low levels. Fish and fish products are the dominant dietary sources; hence mercury is of greater concern in areas

where fish and shellfish account for a major proportion of the diet (Philips 1993, 303). Very high levels (more than 1 mg l⁻¹ wet weight) have been found in the flesh of fish from contaminated waters, resulting in bans on fishing, fish sale, and fish consumption in polluted areas.

Groups of people with high fish consumption rates may accumulate blood-methyl mercury levels associated with a low risk of neurological damage in adults. The health effects of mercury poisoning are essentially irreversible. Symptoms include numbness and tingling, loss of vision and hearing, delirium, and disturbance of gait and speech (Philips 1993, 298). Of particular concern is that methyl mercury is almost completely absorbed from the intestine and stable in the body, and circulates unchanged in the blood. It remains in the body for extended periods of time (biological half-life is estimated at 70-76 days in human and 200 days to two years in fish), penetrates easily through the blood-brain barrier and accumulates in the brain. Pregnant and nursing women are at a greater risk of adverse effects than the general population (WHO 1989b, 33). Methyl mercury easily penetrates the placenta and accumulates in the fetus (Philips 1993, 303), causing critical prenatal exposure which may lead to brain damage (Fitzgerald and Clarkson 1991). Because it is highly fat soluble, methyl mercury also accumulates in mother's milk.

Guidelines. Because the concentrations which may present a public health risk are significantly lower than those that affect the health of the culture species, the guidelines are based on the public health risks. Because the chemical and biological interactions of mercury are so complex, it is not possible to calculate a single mercury criteria for source water that will produce aquaculture products with a mercury concentration less than those which present a risk to public health. Therefore a Phase III pilot study is advisable if total mercury concentrations in fresh or estuarine water are greater than 0.01 ppb or greater than 0.02 ppb in salt water.

Cadmium

Cadmium (Cd) is a highly toxic metal which plays a role in a variety of industrial processes such as electroplating, nickel plating, smelting, engraving, and battery manufacturing. It is also a constituent of easily fusible alloys, soft solder, electrodes for vapor lamps, photoelectric cells, nickel-cadmium storage batteries, pigments and plastics. Inorganic fertilizers such as phosphate fertilizers, sewage sludge used on agricultural land, and tailings from zinc mines are also important sources of cadmium contamination. Cadmium is usually found along with zinc in surface waters, but at much lower concentrations (Svobodová and others 1993, 26). Municipal sewage effluents and sludge are another important source of cadmium in aquatic environments.

Environmental behavior. The predominant form of cadmium in the environment is as the cadmium ion (Cd²⁺). It also can complex with organic matter and particulates to a significant extent (Dojlido and Best 1993, 84-85). In anoxic sediments, cadmium precipitates as cadmium sulfide. Unlike mercury, cadmium does not form organometallic species.

Background levels. In general natural waters contain very low levels of cadmium unless they are polluted. For unpolluted waters of any type, cadmium concentrations generally range from 0.0 to 0.13 ppb.²⁷ Saline water levels are less than 0.2 ppb in estuaries (less than 2.0 in estuarine sediments) and less than 0.15 ppb in coastal areas (less than 1.5 in sediments).²⁸

Effect on fish and shellfish health. The cadmium ion and some organic and inorganic complexes are toxic to fish. Acute toxic exposure of fish damages the central nervous system and parenchymatous organs. Chronic exposure adversely affects the reproductive organs of aquatic organisms, as well as maturation, hatchability, and development of larvae (Svobodová and others 1993, 26). Continuation of exposure causes mortalities at concentrations

considerably lower than the lethal count level (96-hour LC_{50}), probably because the efficiency of the cadmium detoxification mechanism in fish has a limited duration (Lloyd 1992, 84).

However, most of the cadmium which binds with solid particles ends up in sediments where its biological availability is limited and thus less toxic. Calcium also reduces the toxicity of dissolved cadmium, so it is somewhat less toxic in hard water (Lloyd 1992, 84). Because carbon and cadmium compete for binding sites, higher concentrations of carbon dioxide may reduce the bioavailability and hence the toxicity of cadmium.²⁹

Effects on bioaccumulation. Some species have greater capacity for accumulation of cadmium than other species. Unlike mercury, accumulation rates for cadmium vary greatly among groups (Phillips 1993, 304). The bioconcentration factors (concentration in organism/concentration in water) for many species are on the order of thousands. For some mollusks and arthropods, they are on the order of tens of thousands, and on the order of hundreds of thousands for certain tissues (few of which are usually eaten by man).³⁰ Depuration is slow and incomplete, so animals contaminated in culture facilities are not commercially salvageable.

Significant levels of cadmium may be accumulated by bivalve mollusks and certain species of crustaceans (Phillips 1993, 304). In polluted waters, oysters (*Crassostrea gigas* and *C. commercialis*), clams, cockles, and some species of crab (particularly in the brown meat) can accumulate significant amounts of cadmium. The Pacific oyster (*Crassostrea gigas*) has exhibited consistently high concentrations of cadmium, especially in China. Cadmium concentrations in shrimp and prawns are unlikely to be high. Although, studies of *Penaeus japonicus* have revealed high concentrations in areas where fin fish concentrations were comparatively low. In marine vertebrates, cadmium tends to accumulate in the kidneys, leaving the concentration low in the axial muscle tissue.³²

Effects on human health. Cadmium is exceptionally persistent in humans, and even low levels of exposure may result in considerable accumulation over time especially in the kidneys (WHO 1989b, 29). The major symptoms of cadmium poisoning, also known as itai-itai syndrome, are softening of the skeletal bones, pseudo-fractures of the bones, possible skeletal deformation, and kidney damage (Phillips 1993, 299). Subclinical effects include liver and renal tubular dysfunction (Phillips 1993, 300, 304).

Exposure is likely to vary among individuals depending on food preferences. Bivalve mollusks (oysters and clams), some crustaceans, kidneys and livers of terrestrial animals, and tobacco are common pathways of cadmium exposure for humans (Phillips 1993, 304). While cadmium poisoning has not been known to occur as a result of consumption of fisheries products, significant concern exists over this possibility.

Guidelines. Listed in table 3.1 are guidelines for cadmium in source water. Meade's (1989) cadmium criteria of 0.5 ppb for soft water and 5 ppb for hard waters are good for most aquaculture with the exception of mollusks. Linear uptake of cadmium was recorded for mollusks growing in 5 ppb of hard saline water (UNEP 1985, 11). Therefore a more conservative upper limit of 0.5 ppb, regardless of the hardness, is recommended for mollusks.

Lead

The major sources of lead (Pb) to aquatic systems include atmospheric deposition of exhaust from vehicles, disposal of batteries, lead ore mine wastes, lead smelters, sewage discharge, highway runoff, and agricultural runoff from fields fertilized with sewage sludge.

Environmental behavior and background levels. At pH 6 the lead ion (Pb^{2+}) and hydroxide species dominate. At higher pH, lead hydroxide and carbonate species begin to dominate. Lead also commonly forms sulfate and carbonate

Table 3.1 Maximum cadmium concentrations for aquaculture

Species	Concentration (ppb)	Comment	Reference
Salmonids	< 0.2		Svobodová <i>et al.</i> 1993
Salmonid hatcheries	< 0.4 < 3.0	Alkalinity < 100 mg l ⁻¹ Alkalinity > 100 mg l ⁻¹	Piper <i>et al.</i> 1982
Cyprinids	< 1.0		Svobodová <i>et al.</i> 1993
Crustaceans	< 2.0		UNEP 1985
Freshwater	< 1.1		USEPA 1986
Saltwater	< 9.3		USEPA 1986
General guidelines	< 0.5 < 5.0	Alkalinity < 100 mg l ⁻¹ Alkalinity > 100 mg l ⁻¹	Meade 1989
Human drinking water	< 10.0		Maryland 1993

precipitates. It also forms complexes with organic matter and particulates. Dissolved lead concentrations in the environment are generally low due to either precipitation of carbonate species or adsorption to particulate matter (Dojlido and Best 1995, 109–10). There is some evidence that lead forms organometallic compounds in natural systems which can accumulate in fish (Schmidt and Huber 1976). The background levels of dissolved lead in surface waters rarely exceeds 20 ppb (Dojlido and Best 1993, 110).

Effects on fish and shellfish health. Chronic lead toxicity in aquatic organisms leads to nervous system damage while acute toxicity causes gill damage and suffocation (Svobodová and others 1993, 27). Chronic lead toxicity is easily identified in fish by the blackening of the fins (Dojlido and Best 1993, 112). The toxicity of lead is dependent on the alkalinity, hardness and pH of the water. Toxicity is decreased by high alkalinity (that is, high calcium carbonate) because calcium carbonate competes for uptake at the gill surface (Lloyd 1992, 39). The solubility of lead and thus its toxicity is lower in hard waters than in soft waters (Dojlido and Best 1993, 112). For the same reason, lead toxicity is higher at lower pH levels which would be common particularly at ponds bottoms and among benthos and nutrients (Svobodová and others 1993, 27).

Effects on bioaccumulation. Background levels are low in most marine products and unlikely

to be a public health threat (Phillips 1993, 305). However mollusks are known to accumulate high concentrations of lead in polluted areas (Pastor and others 1994, 53). The half-life of lead in marine organisms is shorter than the half-lives of other heavy metals. Lead in black-lip oysters has a half-life of 26 to 34 days. In 40 days mussels lose 33 percent of their accumulated. It is believed that the rate of lead depuration is dependent upon the initial exposure conditions and detoxification mechanism (UNEP 1985, 35).

Effects on human health. As mentioned earlier, fish and shellfish are not a major pathway for lead exposure to human populations. The effects which primarily arise from exposure to exhaust fumes includes impaired neurologic and motor development and damage to kidneys (Dojlido and Best 1993, 112–13). Severe lead poisoning can also occur in cases where lead-based paints are ingested.

Guidelines. The lead criteria in table 3.2 represent the range of opinions regarding maximum concentrations of lead in source water. The permissible level of lead in drinking water is also included for comparison. However, saltwater mussels (*Mytilus edulis*) have been shown to accumulate significant concentrations of lead in water with a concentration of 10 ppb; so it is questionable whether any of the criteria above are conservative enough for mollusks (UNEP 1985, 35). The safest strategy is to conduct a

Table 3.2 Maximum lead concentrations for aquaculture

Species	Lead concentration	Reference
Salmonids	4.0–8.0 ppb < 4.0 ppb annual mean; hardness < 50 mg l ⁻¹ < 0.0 ppb annual mean; hardness 50–150 mg l ⁻¹ < 20.0 ppb annual mean; hardness > 150 mg l ⁻¹	Svobodová <i>et al.</i> 1993 EC 1979
Cyprinids	< 70.0 ppb < 50.0 ppb annual mean; hardness < 50 mg l ⁻¹ < 25.0 ppb annual mean; hardness 50–150 mg l ⁻¹ < 250.0 ppb annual mean; hardness 150–250 mg l ⁻¹	Svobodová <i>et al.</i> 1993 EC 1979
Freshwater	< 3.2 ppb	USEPA 1986
Saltwater	< 8.5 ppb < 5.6 ppb	USEPA 1986 Maryland 1993
All species	< 20.0 ppb	Meade 1989
Drinking water	< 50.0 ppb	Maryland 1993

Phase III pilot study if lead concentrations in proposed source water exceed 3.2 ppb for freshwater or 5.6 ppb for saltwater.

Copper

Copper (Cu) was formerly used in antifouling paints, though it has largely been replaced by organotin. By leaching from paints on the hulls of ships, copper has entered the aquatic environment (Lloyd 1992, 92). In addition copper is used as fungicides and algicides. Mining is also an important source of copper in the aquatic environment.

Environmental behavior. Copper species in natural waters commonly include the cupric ion (Cu²⁺), and copper hydroxide and carbonate complexes. In addition, copper forms strong complexes with dissolved organic matter and particulate matter. These complexes typically control the aqueous copper and/or cupric ion concentration in freshwater systems. Precipitation of copper carbonate may also control the concentration at higher pH levels. In seawater there is evidence that complexation to solids and organic matter is less due to the high concentration of ions competing for complexation sites. In bottom sediments, copper can precipitate out as sulfides, hydroxides and carbonates.³³

Background levels. Concentrations of copper in water are typically around 2 ppb. Higher concentrations occur in polluted areas (Dojlido and Best, 1993, 66).

Effect on fish and shellfish health. Copper has a low toxicity to mammals and does not bioaccumulate readily. However copper is very toxic to aquatic organisms. Therefore rather than causing a human health risk, the main concern regarding copper contamination is its toxicity to aquatic organisms.

Copper is most toxic to aquatic organisms in its cupric ion form. Hardness and dissolved organic matter reduce the amount of cupric ion and thus reduce the toxicity of copper. In hard water, copper forms carbonate precipitates and is very slow to redissolve. Also, calcium in hard waters competes with copper for binding sites, further reducing toxicity. Dissolved organic matter binds strongly with copper resulting in reduced cupric ion concentration and thus lower toxicity.

Guidelines. The maximum recommended concentrations for copper in source water range from 1 to 10 ppb or more depending on the physical and chemical properties of the water and the species of the fish (Svobodová 1993, 25). Listed in table 3.3 are the European Union (EU)

Table 3.3 Maximum copper concentrations for production of salmonid fish

Species	Copper concentration
Salmonids	< 1 ppb; hardness 0-50 mg l ⁻¹ < 6 ppb; hardness 50-100 mg l ⁻¹ < 10 ppb; hardness 100-250 mg l ⁻¹ < 28 ppb; hardness > 250 mg l ⁻¹

Source: EU 1979.

guidelines specifically for salmonids. The following are general copper concentration guidelines collected from different literature sources: less than 2.9 ppb for saltwater; less than 6 ppb for soft freshwater (alkalinity less than 100 mg l⁻¹); less than 12 ppb for hard fresh water alkalinity greater than 100 mg l⁻¹.³⁴

Aluminum

Aluminum (Al) is among the most abundant naturally occurring metals. Its most common forms in the environment are as aluminosilicates or aluminum oxides. Anthropogenic emissions to water include its use as a coagulant in water treatment. It is also commonly used in chemical industries (Dojlido and Best 1993, 100).

Environmental behavior and background levels. Aluminum is more soluble at pH below 6 than at higher pH where it precipitates as aluminum hydroxide (Svobodová and others 1993, 23). Generally at pH levels common to natural waters (pH 5 to 9), aluminum concentrations are low due to the low solubility of aluminum hydroxide. Normal concentrations of dissolved aluminum in natural waters with near neutral pH and low concentration of complexing agents range from 0.0003 ppb to 0.3 ppb.³⁵ Acidified waters would have higher dissolved aluminum concentrations. Complexing agents such as humic acids would increase the solubility of aluminum, thus increasing the dissolved aluminum concentration.

Effects on fish and shellfish health. The toxicity of aluminum to fish is dependent upon the

speciation which in turn is pH dependent. Maximum toxicity occurs at pH 5.³⁶

Effects on bioaccumulation and public health. Fish will die from aluminum poisoning long before they would be able to accumulate concentrations which would be harmful to humans. Therefore bioaccumulation is not a major concern. If exposed, there is very little cause for concern. Aluminum which does accumulate in the body is stored in the heart, spleen and bone, and has not proven to be a serious health risk. It should be noted though that there is a possible but unproven association between aluminum intake and disorders such as Alzheimer's disease (WHO 1989b, 27).

Guidelines. A guideline for aluminum in source water is less than 10 ppb (Meade 1989).

Chromium

Chromium (Cr) is principally used in plating and chrome alloy production. Chromium is also used in pigments, paints, ceramics, textile dyes, fungicides, fireproof bricks and catalysts. Chromate compounds are also used for corrosion control in heating and cooling systems (Dojlido and Best 1993, 175).

Environmental behavior and background levels. Under reduced conditions chromium is in the ion form, Cr³⁺. Under oxidizing conditions such as those commonly found in an aquaculture operation, it is in the hexavalent (Cr⁶⁺) form. A large proportion of chromium in natural waters is found associated with suspended solids and sediment. In natural waters chromium typically has concentrations less than 5 ppb and they rarely get above 20 ppb (Dojlido and Best 1993, 175-76). Chromium can also bioaccumulate in aquatic organisms.

Effects on fish and shellfish health. Chromium is highly toxic to aquatic organisms, especially in the hexavalent form.³⁷ The toxicity of chromium is greater in soft, acidic water (Svobodová and others 1993, 24). Therefore chromium poisoning

is less of a problem in marine waters, and background levels are low in most marine organisms (Phillips 1993, 305). The 96-hr LC_{50} for salmonid fish ranges from 3.3 to 65 mg l⁻¹.³⁸ For longer exposures it was found that a concentration of 13 ppb adversely affected the growth of rainbow trout.³⁹

Chromium is not very toxic to humans. There is little evidence that significant exposure can occur via the ingestion of seafood products. There have been some incidences where large exposures via inhalation of salts caused lung cancer (Förstner and Wittman 1981, 25). Table 3.4 lists water quality criteria for chromium in aquaculture.

Nickel

Nickel (Ni) is introduced to surface waters through effluents from metal plating and ore processing facilities. It is also emitted by the combustion of petroleum products and is used to make batteries.

Environmental behavior and background levels. The dominant form of nickel in aquatic systems is Ni²⁺. It forms moderately strong complexes with humic acids and can adsorb to particulates. However, in general, nickel is found predominantly in the dissolved form in natural

waters (Dojlido and Best 1993, 201). Typical concentrations of nickel in surface water ranges from 1–3 ppb with higher concentrations (10–50 ppb) in industrialized areas.⁴⁰

Effects on fish and shellfish health. Nickel is only moderately toxic to fish. For salmonid culture, nickel has a 96-hr LC_{50} value of 8 mg l⁻¹ in soft waters and 50 mg l⁻¹ in hard waters.⁴¹

Effects on bioaccumulation. Fish have little capacity for bioaccumulation of nickel. Invertebrates have been shown to accumulate nickel (EIFAC 1984, 6–9).

Effects on human health. At high doses nickel can be carcinogenic and teratogenic to humans (Dojlido and Best 1993, 202).

Guidelines. Recommended water quality criteria are: less than 10 ppb (95 percentile less than 30 ppb) for soft water (20 mg l⁻¹ CaCO₃) and less than 40 ppb (95 percentile less than 120 ppb) for hard water (320 mg l⁻¹ CaCO₃).⁴²

Silver

The main industrial sources of silver (Ag) are ore processing, photography, dentistry, and electronics. In industrialized areas anomalously high concentrations of silver can be found in surface waters wherever human beings are found. In fact silver is often a good tracer for sewage.

Environmental behavior and background concentrations. Common aqueous forms of silver under aerobic conditions are the silver ion (Ag⁺) in freshwater and silver chloride complexes in seawater (Stumm and Morgan 1981, 372). It also readily forms precipitates such as silver sulfide, silver oxide, silver chloride and silver nitrate (Dojlido and Best 1993, 70). Mollusks, such as oysters, accumulate silver quickly, but take a long time to depurate. Typical concentrations of silver in surface waters in the United States range from 0 to 1 ppb (Durum and Haffty 1961).

Table 3.4 Maximum chromium concentrations for aquaculture

Species	Chromium concentration
Salmonid	< 5 ppb annual mean; Hardness 0–50 mg l ⁻¹ < 10 ppb annual mean; Hardness 50–100 mg l ⁻¹ < 20 ppb annual mean; Hardness 100–200 mg l ⁻¹ < 50 ppb annual mean; Hardness > 200 mg l ⁻¹
Cyprinid	< 150 ppb annual mean; Hardness 0–50 mg l ⁻¹ < 175 ppb annual mean; Hardness 50–100 mg l ⁻¹ < 200 ppb annual mean; Hardness 100–200 mg l ⁻¹ < 250 ppb annual mean; Hardness > 200 mg l ⁻¹
General guidelines	< 210 ppb chromium (III) < 11 ppb chromium (VI) in freshwater < 50 ppb chromium (VI) in saltwater

Sources: EU 1979 and USEPA 1993.

Effects on fish and shellfish health. Silver is highly toxic to aquatic life. Its toxicity is dependent upon which salt is present. Silver nitrate is most toxic followed by silver chloride and iodide, sulfide, and thiosulfate. Concentrations as low as 0.5 ppb have caused mortalities and interfered with the hatching of rainbow trout.⁴³

Effects on human health. Silver can be absorbed by skin tissue. When this occurs in large amounts, discoloration of both skin and eye tissue, a condition known as argyria, can result (Förstner and Wittman 1981, 16).

Guidelines. Areas with high silver concentrations should be avoided for culture of mollusks. Guidelines for silver concentrations in source water are: less than 0.12 ppb for freshwater and less than 2.3 ppb for saltwater (Maryland 1993, 11).

Tin

Industrial sources of tin (Sn) include processing ore and manufacturing paint and rubber products. Sources of organotin include most predominantly the use of tributyl tin (TBT) as an antifouling paint for boats. It can also come from plastics industries where it is used as a catalyst, fungicide, and disinfectant (Dojlido and Best 1993, 107). There are also tin-based molluscicides that are often excessively used to control snail populations (Acosta and Pullin 1991).

Environmental behavior and background levels. In natural waters under aerobic conditions, tin is most commonly complexed with hydroxides.⁴⁴ In natural waters, TBT remains in a slowly degrading toxic form which accumulates in sediments (Lloyd 1992, 92). Typical concentrations of tin in natural waters are very low, ranging from approximately 0 to 2 ppb (Durum and Haffty 1961). Because organotins do not occur in nature, levels of organotin should be negligible unless contamination exists. Most TBT contamination occurs in the marine environment, but high concentrations can also occur

in freshwater areas where there is considerable boating activity, especially in marinas (Lloyd 1992, 92).

Effects on fish and shellfish health. Tin, which is of low toxicity to mammals, is toxic to aquatic organisms (Phillips 1993, 306). A toxic level has been reported at 2 mg l⁻¹ for fish (Liebman 1958). Organotin compounds are considerably more toxic than tin and are of considerable concern as a result.

Effects on bioaccumulation. Organotin compounds readily bioaccumulate in aquatic organisms (Dojlido and Best 1993, 107).

Effects on human health. Gastric irritation is the main human health problem associated with consumption of foods containing elevated levels of tin (WHO 1989b, 34). Most of the tin ingested by humans is derived from packaging in tin cans. Fisheries products are considered a negligible source of tin in the human diet. However standards for tin in fish and shellfish do exist and can be considered directly if a Phase III study is pursued.

Guidelines. A water quality standard for fish for tin is 2 mg l⁻¹.⁴⁵ For organotins, sediments with TBT concentrations of 1 ppb are toxic to clams (Furness and Rainbow 1990, 118). Proposed environmental quality standards for fish for organotins are 0.02 ppb for tributyl tin and triphenyl tin in freshwater fish.⁴⁶ Other standards state TBT concentrations in source water should be less than 0.026 ppb for freshwater and less than 0.010 ppb for saltwater (Maryland 1993, 11).

Zinc

Zinc (Zn) enters surface waters primarily as a result of discharges from metal treatment plants, chemical plants, and foundries (Dojlido and Best 1993, 79). Mining can also be a source.

Environmental behavior and background levels. In low alkalinity waters, zinc exists as the zinc

ion (Zn^{2+}) and hydroxide complexes. In high alkalinity waters, it forms complexes with carbonate and sulfate. Zinc can precipitate at high pH as zinc hydroxide and coprecipitate with calcium carbonate (Dojlido and Best 1993, 80). It also readily forms complexes with organic matter or particulate matter. Ten to seventy-eight percent of zinc in the world's rivers is adsorbed to suspended solids and very little is in the form of precipitates.⁴⁷ The concentration of zinc in surface waters is generally low. Its range in uncontaminated waters is 5 to 15 ppb (Moore and Ramamoorthy 1984).

Effects on fish and shellfish. There is very little evidence to indicate any significant human health effect of zinc. It is however toxic to aquatic organisms. Zinc concentrations less than 100 ppb had little effect on oyster larvae (*Ostrea edulis*), but concentrations of 300 ppb considerably reduced larval growth, and at concentrations of 500 ppb larvae either died or failed to metamorphose (Milne 1972, 165). Hardness (or high calcium concentration) reduces the toxicity of zinc (Lloyd 1992, 79). The LC_{50} (48–96 hours) varies between 0.5 and 5 $mg\ l^{-1}$ for fish (Moore and Ramamoorthy 1984, 82).

Guidelines. Listed in table 3.5 are the EU guidelines for specific fisheries. General guidelines are: less than 50 ppb for warm water hatcheries; less than 110 ppb for freshwater; and less than 86 ppb for saltwater.⁴⁸

Metalloids

Arsenic

The main sources of contamination of arsenic (As) in the environment are smelting, power generation, the burning of crude oil and coal, and washing of products such as detergents (Dojlido and Best 1993, 144). Arsenic is commonly used in insecticides, herbicides and wood preservatives. There are also some natural groundwater sources of arsenic from arsenic ores and volcanic activity which can reach

Table 3.5 Maximum zinc concentrations for aquaculture recommended by the European Union

Species	Hardness ($mg\ l^{-1}$)	Annual average (ppb)	95th percentile (ppb)
Salmonid fisheries	10	8	30
	50	50	200
	100	75	300
	500	125	500
Coarse fisheries	10	75	300
	50	176	700
	100	250	1,000
	500	500	2,000

Source: EU 1979.

concentrations high enough to cause human health problems.

Environmental behavior and background levels. Arsenic chemistry in water is complex. Arsenic can exist in four different oxidation states depending on whether the conditions are oxidizing or reducing. Arsenic binds strongly to particulate matter, can coprecipitate with iron oxides, and under reducing conditions can precipitate as arsenic sulfide or elemental arsenic. Arsenic also forms methylated species through the action of microorganisms. In natural waters a significant portion of the total arsenic is associated with particulates. For example, 33 percent of the arsenic in Puget Sound and 67 percent in Rhine River is associated with particulates.⁴⁹ Arsenic tends to accumulate in bottom sediments. Unpolluted river waters usually do not contain concentrations greater than 1 ppb.⁵⁰ The coastal waters in the United Kingdom have concentrations of arsenic less than 5 ppb (Musselwhite 1982).

Effects on fish and shellfish health. There is only limited information on the toxicity of arsenic to aquatic species. Based on existing information, arsenic is relatively non-toxic to aquatic organisms. A short-term exposure of approximately 1,000 ppb is necessary for mortalities to occur. However arsenic may affect phytoplankton growth at levels as low as five times the background concentration.⁵¹

Effects on bioaccumulation. The organic forms of arsenic are bioaccumulated in fish and shellfish. However, the bioaccumulation is much less significant than that of methyl mercury. The primary forms of arsenic in fish and shellfish are methylated arsenicals and arsenosugars in primary producers and arsenobetanine in higher organisms. Relatively high concentrations of organic arsenical compounds are present in some seafoods. However the World Health Organization (WHO) has announced that there is little evidence to suggest that people who consume large amounts of seafood suffer adverse effects related to its organic arsenic content. Levels of inorganic arsenic in aquatic organisms are low, frequently below 0.5-1.0 mg l⁻¹ wet weight.⁵²

Effects on human health. The human health effects of arsenic are primarily neurological and nephrological and may linger. The toxicity of arsenic is related to its chemical form. Inorganic forms are toxic to mammals and many organic forms are of insignificant toxicity (Phillips 1993, 300). Human populations consuming large quantities of marine fish contaminated with organoarsenic compounds (weekly intakes of 0.05 mg/kg of body weight) did not experience adverse effects (WHO 1989b, 28). In laboratory tests, rats which consumed enough contaminated fish to produce a daily organoarsenic intake of 3 mg/kg of body weight showed no toxic effects. WHO does not recommend a change in dietary habits due to organoarsenicals in marine fish; however the organization indicates further investigations of the type and levels of organoarsenicals present in marine fish are suggested.

Guidelines. Concentrations of arsenic (III) in source water should not exceed 190 ppb in freshwater and 36 ppb in saltwater (USEPA 1993).

Selenium

The principle sources of selenium (Se) in the environment are the burning of fossil fuels and

cement production (Dojlido and Best 1993, 172).

Environmental behavior and background levels. Like arsenic, selenium exists in the environment in many different oxidation states. Its most common forms in the environment are as selenites and selenates which have similar chemical behavior as sulfites and sulfates. The breakdown of organic matter containing selenium results in the formation of organoselenium compounds. Typical background concentrations of selenium are around 0.1 ppb.⁵³

Effects on fish and shellfish health. Selenium presents few problems for marine organisms, and it may even help in detoxifying accumulated mercury.⁵⁴

Effects on bioaccumulation and human health. Organic forms of selenium can bioaccumulate and are harmful to humans. Selenium is also a necessary nutrient to humans and the difference between the amount that results in a nutrient deficiency and the amount that results in toxicity is very small (Dojlido and Best 1993, 173).

Guidelines. Concentrations of selenium in source waters should not exceed 5 ppb in freshwater and 71 ppb in saltwater (USEPA 1993).

Chlorine

Chlorine (Cl) is discharged into surface waters from municipal and agricultural water treatment operations and from textile and paper plants. Chemical industries which use chlorine gas can also be a significant source. If a source water is taken from a municipal water supply which chlorinates, high chlorine concentrations should be expected.

Environmental behavior and background levels. Upon entering water, chlorine gas dissociates to form hypochlorous and hydrochloric acids. Hypochlorous acid (HOCl) partially dissociates

creating water with some hypochlorite (OCl^-) which is the less toxic species and some HOCl , the more toxic species. The proportion of each species is dependent upon the pH. As pH increases, the proportion of hypochlorite increases until about pH 9 where it dominates. Chlorine commonly reacts to form chloramines in solution. In general the high reactivity of chlorine makes it relatively short lived in aquatic systems.

The amount of chlorine added to municipal water supplies depends upon the pH and the amount of organic matter and complexing agents in the water supply. However, it tends to range between 0.1 to 1.0 mg l^{-1} of residual free chlorine (chlorine which has not reacted with complexes or organic compounds in solution).⁵⁵

Effects. Chlorine and chloramines are very toxic to fish. Concentrations as low as 4 ppb as HOCl can be harmful to fish within four days of exposure (Alabaster and Lloyd 1980, 185).

Guidelines. The USEPA recommends chlorine residuals not exceed 11 ppb in freshwater or 7.5 ppb in saltwater. For freshwater fisheries at a pH of 6, the EU recommends a residual free chlorine concentration of 6.8 ppb or less. Higher pH can tolerate more. However it is more prudent to follow the more conservative general criteria of 3 ppb suggested by some researchers.⁵⁶

Treatment. Addition of sodium thiosulfate is the most effective method for chlorine removal. It takes approximately 7 mg l^{-1} of sodium thiosulfate pentahydrate to remove 1 mg l^{-1} of free residual chlorine. Chlorine also can be removed by simply holding water in a storage reservoir until the chlorine dissipates through exposure to sunlight.⁵⁷

Cyanide

Cyanide (CN^-) may be discharged into surface waters from a variety of industries including coking plants, gasworks, galvanizing plants, and petroleum refineries.

Environmental behavior and background levels. Cyanide in water is typically in the form of hydrogen cyanide, HCN , or the ion form CN^- . The ion form can take on a variety of complexes with metals. These complexes are of varied stability with the most stable complexes forming with iron and cobalt. Because HCN is the most toxic form, it is these complexes which regulate the toxicity of cyanide. Cyanides do not generally occur in surface waters because of their rapid breakdown and evaporation. They are typically found only near discharge points (Dojlido and Best 1993, 208–9).

Effects. Due to the rapid breakdown of cyanide in water, toxicity is of primary concern for fish and shellfish. The toxicity of cyanide is dependent upon the complexes formed with metals in solution. The weaker the complex, the higher the toxicity. Therefore, high concentrations of metals which form strong complexes with CN^- [for example, Ni, Fe (II), Fe (III), CO] would reduce the toxicity of CN^- . Toxicity is also increased by low pH and by high temperature.⁵⁸

Guidelines. Maximum permissible cyanide concentrations range from 0.2 to 20 ppb depending on the compounds involved. Suggested general guidelines are 5 ppb in freshwater or 1 ppb in saltwater.⁵⁹

Organic Compounds

Off-flavor

Odorous organic compounds such as those from petroleum distillates and discharges from paper processing are a common source of off-flavors in fish. Pulp and paper mill wastes contain polymeric lignins, phenolic compounds, mercaptans, terpenes, and other residues of chemically digested wood chips which can contain chlorinated derivatives and degradation products of chlorolignins such as chloroform, carbon tetrachloride, and chloroethylenes. Petroleum products enter waters via discharges from petroleum refineries

or petrochemical industries as runoff contaminated by motor oils and fuels, from wastes and spills of boat fuels, and from oil spills or discharge of ballast water off oil tankers and other large ships. Phenols in source water may also cause off-flavor. Phenols result from discharges of industrial effluents (especially from thermal processing of coal), from petroleum refineries, and from the production of synthetic fabrics.⁶⁰

Effects. The primary effect is on the flavor of the product because fish grown in water contaminated with these compounds will be unpalatable before contaminant concentrations reach an unhealthy level. The exception to this is phenols which can have significant behavioral effects on fish.⁶¹

The majority of off-flavor in fish exposed to petroleum products are caused by unsaturated alkanes, aromatic hydrocarbons, and sulfur containing organic contaminants. However not all petroleum contaminants result in off-flavor. Saturated aliphatic hydrocarbons are not very odorous and do not cause unpalatable flavors in fish (Tucker and Martin 1991, 137).

Phenols act as anesthetics on the central nervous system. Chronic exposure to phenols may result in necrobiotic changes in the brain, parenchymatous organs, circulation system, and gills. The symptoms of phenol poisoning in aquatic species are increased activity, leaping out of the water, loss of balance, and muscular spasms.

Guidelines. Admissible concentrations for oils range between 0.002 and 0.025 mg l⁻¹. Admissible concentrations for phenols are 0.001 mg l⁻¹ for chlorophenol, 0.003 mg l⁻¹ for cresol, 0.004 mg l⁻¹ for resorcine, and 0.001 mg l⁻¹ for hydroquinone (Svobodová 1993, 27–28, 35).

The simplest test for off-flavor producing organics requires neither equipment nor reagents: water which tastes or smells unusual may result in off-flavor. Therefore a sensory assessment can often be preferable to chemical analysis in assessment of the source water.

Pesticides

Pesticide is used to refer to any chemical employed to control unwanted nonpathogenic organisms including insecticides, acaricides, herbicides, fungicides, algicides, and even rotenone which is used to kill unwanted fish (Svobodová 1993, 30). Pesticides have traditionally been designed to be not only toxic but persistent. The persistence allows for less frequent application of the pesticide. These properties are precisely the reasons for the environmental concern over pesticides. Pesticides are of concern because of the risks they pose to fish and shellfish health, as well as the risks their bioaccumulation pose to product quality and public health.

Pesticides can be split into seven main categories: inorganic pesticides, organophosphorus pesticides, carbamates, derivatives of phenoxyacetic acid, urea pesticides, pyridinium pesticides, and derivatives of triazine (Dojlido and Best 1993, 234). The chlorinated pesticides are of particular concern due to their persistence and tendency to bioaccumulate in fish and shellfish.

The major source of pesticide contamination in surface waters is runoff from agriculture. Pesticide manufacturing operations can emit wastes with extremely high pesticide concentrations. Because of the persistence of many pesticides, special attention must be made to potential past sources of pesticides in identifying potential contamination sources to aquaculture source water.

Some chlorinated pesticides, namely dichloro-diphenyl-trichloro-ethane or DDT, aldrin, dieldrin, heptachlor, and chlordane are prohibited in the United States and their use continues to decline worldwide.⁶² However they are still used in some developing countries where problems of agricultural pests and insect-transmitted disease are severe and alternative methods are expensive or insufficiently developed.

Environmental behavior. The persistence of pesticides varies depending on the chemical

Table 3.6 Persistence of pesticides

<i>Readily degradable</i> 1/2 life < 2 wks	<i>Slightly degradable</i> 1/2 life = 2-6 wks	<i>Moderately persistent</i> 1/2 life = 6 wks-6 mos.	<i>Persistent</i> 1/2 life > 6 mos.
Captan	Chloramben	Carbofuran	DDT
Carbaryl	Chlorpropham	Carboxin	γ-HCH
Chlorpyrifos	Dalapon	Chlordane	Aldrin
Dichlone	Diazinon	Chlorfenvinfos	Dieldrin
Dicrotophos	Disulfoton	Chloroxuron	Heptachlor
Endotol	Fenuron	Dimethoate	Isodrin
Endosulfan	MCPA	Diphenamid	Monocrotophos
Fenitrothion	Methoxychlor	Diuron	Benomyl
Malathion	Monuron	Ethion	
Methiocarb	Phorate	Fensulfothion	
Methylparathion	Propham	Linuron	
Parathion		Prometion	
Phosphamidon		Propazine	
Propoxur		Simazine	
2,4-D		Toxaphene	

Source: McEwan and Stephenson 1979.

structure. In general the more insoluble pesticides such as organochlorine pesticides tend to be more persistent, while the water soluble pesticides tend to be less persistent (Dojlido and Best 1993, 239–41). Table 3.6 shows the relative persistence of a range of pesticides.

The primary mechanism of pesticide degradation is biological, however chemical and photochemical degradation also occurs. The processes controlling biodegradation are complex and poorly understood. Among the limiting processes are presence of organisms which can degrade the chemicals, existence of conditions in which the organisms can grow to significant populations, and availability of sediment-bound pesticides to the organisms. Another process affecting the fate of pesticides is their high affinity for particulates, especially those containing organic matter. This is particularly true for the pesticides with low solubility such as the organochlorine pesticides. As a result, these pesticides commonly accumulate in bottom sediments where biodegradation is often slow because of factors such as reduced bioavailability, non-ideal redox conditions, or nutrient limitations.

Effects on fish and shellfish health. The toxicities (96-hr LC₅₀) and safe levels of selected chlorin-

ated pesticides are listed in table 3.7. The toxicity of a pesticide can be reduced by high concentrations of particulate matter. Adsorption to these particulates, as well as sediments, reduces the availability and toxicity of a given pesticide. Pesticides also affect aquaculture species indirectly through their toxicity to phytoplankton.

Table 3.7 Toxicity to aquatic life of selected chlorinated hydrocarbon insecticides

<i>Pesticide</i>	<i>96-hr LC₅₀</i> <i>(ppb)</i>	<i>Safe level</i> <i>(ppb)</i>
Aldrin	0.20–16.0	0.003
BHC	0.17–240.0	4.0
		0.08
Chlordane	5.0–3,000.0	0.01
		0.0043 (fresh)
		0.004 (salt)
DDT	0.24–2.0	0.001
Dieldrin	0.20–16.0	0.003
		0.0019
Endrin	0.13–12.0	0.004
		0.0023
Heptachlor	0.10–230.0	0.001
		0.0038 (fresh)
		0.0036 (salt)
Toxaphene	1.0–6.0	0.005
		0.0002

Source: Boyd 1990 and USEPA 1993.

Herbicides are particularly toxic to phytoplankton (Boyd 1990, 166).

Effects on bioaccumulation. Many pesticides, including most significantly chlorinated pesticides, have a low solubility in water; however they readily dissolve in hydrophobic environments such as the fats of aquatic organisms. In general lower solubility results in a higher tendency for a pesticide to accumulate in fish and shellfish. Efforts to experimentally quantify the bioconcentration factors (BCF) have not yielded exact results due to the variability in experimental conditions. The BCF equals concentration of pesticide in organism divided by concentration of pesticide in water. However they have yielded general BCF ranges for a particular compound. Listed in table 3.8 are the solubility of selected pesticides and the corresponding ranges of experimentally derived BCF for fish.

Effects on human health. Organochlorine pesticides are absorbed in humans by the gastrointestinal tract, and some may also be absorbed through the skin. The toxic mechanisms are not yet fully understood, but the major toxic action of organochlorine pesticides is on the central and peripheral nervous system. Exposure to chlorinated cyclodiene insecticides (that is, aldrin, dieldrin, endrin, chlordane, heptachlor, endosulfan, and isodrin) causes headaches, dizziness, nausea, vomiting, jerking muscles, and convulsions. In addition many pesticides are suspected carcinogens.⁶³

Guidelines. The safe levels for selected pesticides in table 24 include only a partial list of the hundreds and potentially thousands of commercially available pesticides. If the pesticides used in the watershed from which source water is derived are not among those listed, further investigations should be conducted to determine permissible levels.

Depending on the pesticides of concern, the testing required to determine permissible levels may range from simple to complex. Because many persistent pesticides bind strongly to sediments and suspended particulate matter, testing of concentrations which occur in solution may be misleadingly low in comparison with their bioavailability (Lloyd 1992, 90). Therefore if the presence of persistent pesticides is suspected in source water or sediments, a Phase III field study should be conducted to determine the effects of potential pesticide accumulation on culture species and consumers.

Treatment. Options include those used in treatment of municipal water supplies such as reverse osmosis, ion exchange, air stripping, adsorption, and oxidation. However these are often very expensive. Finding another source water may be the most viable choice.

Water from an uncontaminated source can be contaminated by insecticides after it is introduced into culture facilities. Pesticides sprayed onto crops may drift over considerable distances to ponds and canals (Boyd 1989, 47). Box 3.1 describes measures to prevent pesticides from contaminating the aquaculture ponds.

Table 3.8 Pesticide solubility and experimentally derived bioaccumulation factors in fish

Pesticide	Solubility in water (mg l ⁻¹)	BCF in fish	References
Aldrin	0.02	3,890–10,715	Suntio <i>et al.</i> 1988 and Howard 1991
Atrazine	33	3–10	Khan 1977
BHC	low	1,160–3,740	Khan 1977
Chlordane	0.1	5,200–38,000	Worthing 1987 and Howard 1991
Dieldrin	0.17	3–6,000	Suntio 1988 and Howard 1991
Endrin	0.00025	1,335–10,000	Biggar and Riggs 1974 and Howard 1991
Heptachlor	0.18	5,744–21,379	Biggar and Riggs 1974 and Howard 1991
Toxaphene	0.55	3,100–33,300	Murphy <i>et al.</i> 1987 and Reish <i>et al.</i> 1978

Note: BCF factors partially taken from Howard (1991), in which literature values are included for a long list of pesticides. Ranges listed here were taken from the literature values quoted for fish that did not specify an unusually short equilibrium time (that is, on the order of hours.)

Box 3.1 Protecting aquaculture ponds from pesticides

- Place ponds a considerable distance from pesticide treated fields.
- Plant trees or other tall plants between pesticide treated fields and aquaculture facilities to intercept airborne drift of sprayed pesticides.
- Construct topographic barriers (ditches or terraces) to prevent agricultural runoff from entering ponds.
- Use proper methods of pesticide application to fields.
- Properly dispose of all pesticides and pesticide containers.

Source: Boyd 1990.

Antibiotics and Antimicrobials

Agriculture is one example of industries requiring control of microbes which may contaminate source water with unwanted antibiotics and antimicrobials. Iodine, for example, is often used in veterinary drugs, agricultural chemicals, and sanitizing solutions (WHO 1989b, 32). These chemicals may damage the natural micro-biological communities which are necessary for the health of the culture species; or they may disturb the natural microbiological environment, creating an opening for opportunistic pathogens.

Bioavailability is a particularly important issue for antibiotics and antimicrobials. Testing procedures for these compounds are so sensitive that even a few molecules can be detected. However molecules which are bound to sediments and other substrates, and thus biologically unavailable, must be detached in order to be detected. Therefore the levels which are shown by testing may be representative of many antibiotic and antimicrobial chemical complexes which are not biologically active.⁶⁴

Petroleum Hydrocarbons

As components of liquid and gaseous fuels, hydrocarbons are among the most widely

processed and distributed chemical products in the world. Primary sources include runoff from roads and discharge from industries using oil (Dojlido and Best 1993, 231). As mentioned earlier, the major concern of petroleum hydrocarbons to aquaculture is producing off-flavor. Crude oil, either released from tankers at sea or spilt accidentally at oil fields or shore terminals, is a major pollutant in the intertidal zone which can devastate oyster beds (Milne 1972, 163). The risks of potential aquaculture source water taken from areas with high oil tanker traffic should be considered carefully.

Polychlorinated Biphenyls

Polychlorinated biphenyls (PCB) were heavily used in transformers and capacitors of heavy electrical equipment as lubricants for compressors and in the production of varnishes, dye-stuffs and plastics (EIFAC 1993, 28). Common worldwide PCB trade names are Aroclor (USA), Clophen (Germany), Delor (Czechoslovakia), Kaneclor (Japan), and Savol and Sovtol (Russia and the former Soviet republics).⁶⁵ In the 1970s severe restrictions were made on its production and as a result worldwide production has gone down drastically. However PCB is considered among the most persistent pollutants and contamination is widespread. Because of their persistence, it is of particular importance to identify older companies which may have been producing the chemical in order to identify if PCBs are potentially contaminating the source water. It should also be noted that PCBs can travel great distances and therefore industries outside the immediate locality may be contaminating the source water of concern.

Environmental behavior. PCBs are extremely persistent in the environment. Although they can be biodegraded, degradation is slow under natural conditions. The PCBs are able to volatilize from water; however the more common destiny for these molecules is in sediments and body tissues. This is due to their extremely low solubility which encourages adsorption to sedi-

ments and accumulation in the fat tissues of fish and mammals. As a result, concentration of PCBs in the water column are typically much lower than in the sediments (Dojlido and Best 1993, 183, 282).

Effects on fish and shellfish health. Chronic exposure to low levels of PCBs may result in skeletal deformities, skin and fin damage (possibly disintegration), damage to the liver and gonads, high mortality during hatching, and high mortality of early fry (Svobodová 1993, 29). The eggs and larvae of aquatic organisms are more sensitive to these pollutants. The solubility and thus toxicity of PCBs are enhanced by increases in temperature.

Effects on bioaccumulation. Because of their low solubility in water and high solubility in fat, these compounds have a large tendency to accumulate in the food chain, especially in lipid rich eggs and fatty fish such as eels. The BCF for PCBs in aquatic organisms ranges from 10^3 to 10^5 . Shellfish and mussels are known to accumulate PCBs in contaminated waters.⁶⁶

Effects on human health. When ingested, less highly chlorinated PCBs are metabolized in the liver and excreted, but more highly chlorinated biphenyls are metabolically stable and accumulate in body fat. However the toxicity of PCBs to humans is generally low. In Japan in 1968 an accidental consumption of PCB-contaminated edible oil by 1,000 people resulted in no mortalities but adverse health symptoms were observed for three years.⁶⁷

Guidelines. Because there are over 200 PCBs with individual toxicological properties which are often mixed together, it is difficult to determine toxicity standards for either human or aquatic species. Most toxicity tests are carried out on commercial formulations which are normally identified by the extent to which they are chlorinated rather than by the PCBs that they contain. Differential uptake of the individual components leads to a different ratio being found in the organisms when com-

pared to that in the tested formulations (Svobodová 1993, 28).

General water criteria for aquatic organisms as set by the USEPA are less than 0.014 ppb for freshwater and less than 0.03 ppb for saltwater. Meade (1989) suggests that levels up to 2 ppb may be acceptable. Due to their high toxicity, if levels of any PCBs exceed those set out by the USEPA, a Phase III pilot project should be pursued to identify and quantify a number of key types of PCBs for an expert evaluation of the potential hazard.⁶⁸

Dioxins and Furans

Dioxins is a general term for 75 different polychlorinated dibenzo-o-dioxins. Similarly, furans is a general term for 135 different polychlorinated dibenzofurans. Furans are typically found in conjunction with dioxins.

Dioxins and furans can enter water via the wastewater of industries such as wood processing plants, pulp and paper mills, tanneries, and the production of pesticides and wood preservatives. Also, combustion of wastes, coal and chlorinated pesticides can produce dioxins and furans (Dojlido and Best 1993, 287).

Environmental behavior. Dioxins and furans are widespread in the water environment. Sediments are a major sink for these compounds. Their biodegradation is slow and because of their low solubility, they readily adsorb to sediments.

Effects on fish and shellfish health. In rainbow trout, coho salmon, guppy, and pike, chronic exposure to tetrachloro dioxin (TCDD) through diet or water caused decreased growth and caused fin necrosis and death.⁶⁹

Effects on bioaccumulation. Dioxins and furans have low solubility and therefore are capable of bioaccumulation in fish. Bioaccumulation factors up to 10,000 have been reported (Isensee 1978).

Effects on human health. Of the dioxins the 2, 3, 7, 8 tetrachloro isomer (2,3,7,8 TCDD) is the

most toxic. The primary human health effects of dioxins are chloracne and possible birth defects. They have also been shown to affect the liver and nervous system.⁷⁰

However, it should be noted that the effects of dioxins and furans in the above areas are not certain and a point of great controversy in politics and in the scientific community.

Guidelines. It is difficult to prescribe guidelines considering the controversial nature of dioxin effects. It is recommended that dioxins be evaluated on a case-by-case basis. If their presence is suspected, a Phase III field study should be pursued.

Pathogens and Biological Contaminants

High concentrations of pathogenic organisms are commonly found in waters polluted by human sewage and animal wastes. Thus a major source of contamination is sewage outfalls in populated areas and livestock facilities.

Human Pathogens in Fish and Shellfish

In many countries untreated wastewater or animal wastes are used directly in aquaculture; in these cases contamination is of particular concern.

Effects. Human pathogens are of concern in aquaculture because they can accumulate in fish. These organisms do not cause disease in the fish. However, the fish can serve as a vector for the disease thus infecting humans who consume them or handle them. Many pathogens, including salmonella, *E. coli* and *Clostridium botulinum*, have been found to survive in fish tissues (Buras 1990).

Guidelines for fecal coliforms. WHO (1989) recommends that fecal coliform counts in source water not exceed 10^3 per 100 ml. Mara and Cairncross (1989) indicate that in wastewater-fed ponds, concentrations of 10^4 per 100 ml are acceptable for culture of both fish and aquatic macrophytes. They assume that a reduction of

one order of magnitude takes place in-pond, so that in-pond concentrations should be less than 10^3 per 100 ml. If pond temperature and retention time indicate that a higher reduction can be achieved, this guideline may be relaxed. At concentrations above 10^4 and 10^5 per 100 ml, the potential for fecal coliform and other pathogens to invade muscle tissue is very high.⁷¹

Guidelines for total bacteria. The validity of fecal coliform as an overall indicator of bacteriological contamination is debatable, especially in the tropics. Reliance on coliform standards may overestimate potential health risks, unduly burdening developing countries in their efforts to develop shellfish resources in tropical waters (Rice 1992, 195). Some researchers recommend that the concentration of total bacteria (not total coliforms or fecal coliforms, but standard plate count per ml) be used to assess the risk of microbial contamination. They point out that if total bacteria reaches 1.0 to 5.0 multiplied by 10^4 per ml, then bacteria are likely to appear in muscle tissue (Buras and others 1985).

Guidelines for specific pathogens and parasites. Other pathogens associated with human diseases such as salmonella, streptococcus, *Aeromonas*, *Pseudomonas*, *Klebsiellae*, and *Escherichiae* are often found in the gut of fish cultured in wastewater, but rarely in the muscle tissues or visceral organs. WHO recommends that salmonella count in source water not exceed 10^3 per 100 ml. Mara and Cairncross (1989) recommend that the concentration of viable trematode eggs (arithmetic mean number per liter or kg) be equal to zero, because the only feasible means of controlling *Clonorchis sinensis*, *Fasciolopsis buski*, and *Schistosoma japonicum* (species which are endemic to Asia) is to remove all viable eggs before the wastewater is applied to ponds.⁷²

Botulism, typhoid, hepatitis, cholera, non-specific gastroenteritis, and a host of other diseases may also result from ingestion of raw or insufficiently cooked fish and shellfish. Therefore if wastewater or other sources which are likely to be contaminated with pathogens are used, source water should be tested for a range

of pathogens which might influence project viability.

Standards for shellfish. The United States has established standards for waters that can be used to culture or harvest shellfish. For these waters the total coliform median or geometric mean most probable number (MPN) of the water should not exceed 70 per 100 ml and not more than 10 percent of the samples can exceed an MPN of 230 per 100 ml for a 5-tube decimal dilution test (or an MPN of 330 per 100 ml for a 3-tube decimal dilution test). In addition the fecal coliform median or geometric mean MPN of the water should not exceed 14 per 100 ml and not more than 10 percent of the samples can exceed an MPN of 43 per 100 ml for a 5-tube decimal dilution test (or an MPN of 49 per 100 ml for a 3-tube decimal dilution test).⁷³

Water treatment. Wastewater usage can be treated through traditional wastewater treatment processes. These processes can be a combination of primary sedimentation, activated sludge, biofiltration, aerated lagoon, oxidation ditch, disinfection, waste stabilization ponds, or effluent storage reservoirs. Treated wastewaters have been shown usable for aquaculture and, in some cases, as a better alternative than the local contaminated surface water.⁷⁴

In addition, chlorination of aquaculture ponds to remove pathogens can be performed. The chlorine dose will vary depending on pH and the concentration of organic matter and ammonia. However, when chlorinating aquaculture ponds, one has to be careful the concentrations of chlorine are reduced below toxic levels before the fish are exposed to the disinfected water (Boyd 1996, 44).

Treatment by depuration of shellfish. Filter-feeding shellfish grown in polluted or low-quality water accumulate pathogenic micro-organisms and have to be depurated before sale, especially in areas where shellfish is eaten raw or partially uncooked. Depuration also reduces the risk of viral pathogens, such as hepatitis, which are often transmitted through oysters and clams.

Because such pathogens are difficult and expensive to monitor, standards are set for depuration processes rather than for the concentration of pathogens in the flesh of cultured organisms (Pillay 1992, 104). For example, only shellfish grown from certified operations can be sold on the United States and Canadian markets.

The two most common methods of depuration are relaying in clean water or depuration in specially designed plants. Relaying entails transplanting shellfish into a clean area for a minimum period of time, usually 30 days; however, depuration of highly contaminated shellfish requires longer purging periods and is not feasible on a commercial basis. Depuration plants store the shellfish in tanks of seawater disinfected with filters, chlorine, ozone, or ultra-violet radiation (Pillay 1992, 104). Despite its acceptance in many countries, depuration alone without attention to water quality in the initial growing areas is not sufficient to assure safe shellfish. Careful attention must be given for developing unpolluted areas and culture practices which will minimize the risk of microbial contamination of shellfish.

Phytoplankton and Algal Toxins

Off-flavor. The muddy, earthy flavor of fish grown in fresh or brackish water is one of the most common types of environmental contamination of aquaculture fish; it can often be anticipated by smelling or tasting the source water. This muddy off-flavor, which is easily detected in mild-flavored fish, is not harmful to human health, but can result in lower prices for aquaculture products. Off-flavor in pond-culture fish is characteristic of geosmin, 2-methylisoborneol, mucidone, or similar compounds produced by blooms of actinomycetes and blue-green algae. Algal blooms are often times unpredictable and hard to prevent. The offending algae can be killed with copper sulfate, but the best strategy is to remove the muddy flavor through depuration in clean water prior to harvesting. Catfish, for example, can depurate in 5 to 15 days depending on water temperature and the severity of the off-flavor. Algae which cause

muddy off-flavor do not thrive in saline water (Pillay 1992, 100-1).

Red tide. Red tides (blooms of toxic dinoflagellates) are a major source of fish and shellfish mortality and a serious public health hazard. The most common algal blooms in tropical waters are caused by the dinoflagellate *Pyrodinium bahamense* var. *compressa*.⁷⁵

Shellfish rapidly accumulate these toxins and become vectors of various forms of shellfish poisoning, such as paralytic shellfish poisoning (PSP), diarrhetic shellfish poisoning (DSP), neurotoxic shellfish poisoning (NSP), and amnesiac shellfish poisoning (ASP). Rates of toxin accumulation and depuration vary with species, temperature, and intensity of blooms. Mussels both accumulate and depurate PSP toxins more quickly than other species, while oysters take a longer time to accumulate and to detoxify. Some species have been reported to remain toxic for up to two years. The hard clam or quahog, on the other hand, can avoid toxic algae by burying itself deep within the sand and closing its shell. Scallops are also safe to eat during algal blooms because the part normally eaten, the abductor

muscle, rarely becomes toxic. Depuration is feasible for rapidly detoxifying species. However detoxifying shellfish on a large scale is not economically promising.⁷⁶

Toxic algal blooms. Toxic algal blooms are difficult to prevent or predict. Algal blooms originate in the oceans far from shellfish beds, and the mechanisms which cause them are not well understood. The toxins associated with these algae can cause shellfish to become toxic overnight. These toxins can persist for months after blooms have disappeared, resulting in major economic disasters (Pillay 1992, 105).

Guidelines. Because it is difficult to predict if a given source water will be a victim of algal or phytoplankton blooms, guidelines need to be based on historical monitoring data. If data exist on location and extent of algal or phytoplankton blooms, then it should be determined if the area of the proposed source water is susceptible to blooms. If so, the risks must be considered carefully. The effects may be mitigated by restricting the types of species farmed or the time of year farms can operate using this source water.

Phase III: Field Study

Phase III should be pursued if Phase I or Phase II criteria are not met and the risks are either considered acceptable or a treatment method which is technically and financially viable is found. The purpose of Phase III is to provide a field test of aquaculture operation when the success of the project is in question based on water quality. The field study will help render a decision on whether or not to use the selected source water. In the case where the source water is accepted, any operational problems or adjustments can be anticipated before the project begins. The field study specifically focuses on evaluating the fish growth and health, the contaminant residues in the fish, and the technical and economic feasibility of a treatment operation.

Study Design

There are two options for the type of field study. The more cost efficient method is to find an operating aquaculture facility in the area which is using the same source water and management techniques to grow a similar species. Tests for species growth and health and contaminant residues can then be made on the product of this facility. In addition, a detail design including cost analysis can be made of any proposed treatment processes.

The second option is to set up a pilot study of the aquaculture facility, using the proposed source water, any proposed treatment

processes, and the project species. The fish growth, health, and contaminant residues can then be measured. A design and cost analysis can be made of any proposed treatment processes.

In both cases it is important to emulate the conditions to be used in the final project. This includes not only source water and species but, if possible, the soil. Because quality in surface waters can vary seasonally, it is important to run the study over a representative time period which reflects these changes. Typically this would be one year. In order to make sure the influence of source water quality on project outcome is being tested, efforts should be made to eliminate other possible sources of failure.

Criteria for Fish Growth and Health

Fish should be of sufficient size to be marketable and production should operate at a high enough rate to be profitable. The fish should be sufficiently healthy so disease or its risk is low. The fish should undergo examination for any specific symptoms based on the pollutants present. More general examination for diseases, stress, or abnormalities should be performed. Recent research has pointed to the utility of biomarkers in assessing a potential effect of water quality on fish. These markers, which are listed in appendix table 4, may be of use depending on the pollutant. In particular those measuring stress such as the corticosteroids

teroids/cataecholamines biomarkers have been suggested as a good measure of general stress as a result of water quality problems (Tarazona and Munoz 1995).

Criteria for Contaminant Residues

In the case of fish intended for export, contaminant residues should be sufficiently low to meet the standards of the importing country. For fish intended for consumption locally, standards should be adopted based on protection of public health.

Basis for Standards

Levels of contaminants allowed in food and drinking water are based upon provisional tolerable weekly intake (PTWI) standards. These standards, expressed in micrograms per person or micrograms per person per kilogram of body weight, depend upon the average rate of human bioaccumulation from contaminated foodstuffs. Standards for contaminant residues in food are calculated on the basis of the PTWI, rate of consumption of the foodstuff, and probable extent of exposure to the contaminant via other pathways. PTWI for selected contaminants are listed in appendix table 5.

Fish and Shellfish Intended for Export

For fish and shellfish intended for export, the contaminant residues should meet the standards of the importing country. Appendix tables 6 and 7 list these standards for chemical and

biological contaminants for the United States, Canada, Japan, and the European Union.

Fish and Shellfish Intended for Local Consumption

Because diet and possible exposure to contaminants differ from country to country, standards for contaminant residues set as import standards by some countries in food may not be appropriate for the project area. Both where aquaculture products will be consumed and what product parts will be consumed must be taken into account when considering permissible levels of contaminant residues. If a product is going to be consumed heavily in a local area, the residues will have to be lower to be safe. In addition all edible parts should meet consumption standards and the parts of a fish deemed edible vary from market to market according to custom and taste. Consumers in some regions may eat kidneys, livers, or other organs, while consumers in other regions will eat only muscle tissues. In addition, certain contaminants may accumulate in the kidney, liver, and muscle tissues of a fish at different rates. Hence a single fish may contain some parts which meet standards and others which do not.

If no standards are set for the project area, the above factors should be considered to the extent possible in establishing standards. In arriving at these standards the list of PTWI in appendix table 5 may be useful along with the import standards for different countries listed in appendix tables 6 and 7.

APPENDIX TABLES

Appendix table 1 Effect of biological processes on alkalinity

<i>Process</i>	<i>Alkalinity change for forward reaction</i>	<i>pH change for forward reaction</i>
Photosynthesis (forward reaction) and respiration (reverse reaction)		
(1a) $n\text{CO}_2 + n\text{H}_2\text{O} \rightleftharpoons (\text{CH}_2\text{O})_n + n\text{O}_2$	No change	No change
(1b) $106\text{CO}_2 + 16\text{NO}_3^- + \text{HPO}_4^{2-} + 122\text{H}_2\text{O} + 18\text{H}^+ \{ \text{C}_{106}\text{H}_{263}\text{O}_{110}\text{N}_{16}\text{P}_1 \} + 138\text{O}_2$ "algae"	Increase	Increase
(1c) $106\text{CO}_2 + 16\text{NH}_4^+ + \text{HPO}_4^{2-} + 108\text{H}_2\text{O} \{ \text{C}_{106}\text{H}_{263}\text{O}_{110}\text{N}_{16}\text{P}_1 \} + 107\text{O}_2 + 14\text{H}^+$	Decrease	Decrease
Nitrification		
(2) $\text{NH}_4 + 2\text{O}_2 = \text{NO}_3^- + \text{H}_2\text{O} + 2\text{H}^+$	Decrease	Decrease
Denitrification		
(3) $5\text{CH}_2\text{O} + 4\text{NO}_3^- + 4\text{H}^+ = 5\text{CO}_2 + 2\text{N}_2 + 7\text{H}_2\text{O}$	Increase	Increase
Sulfide oxidation		
(4a) $\text{HS}^- + 2\text{O}_2 = \text{SO}_4^{2-} + \text{H}^+$	Decrease	Decrease
(4b) $\text{FeS}_2(\text{s}) + 3.75\text{O}_2 + 3.5\text{H}_2\text{O} \Rightarrow \text{Fe}(\text{OH})_3(\text{s}) + 4\text{H}^+ + 2\text{SO}_4^{2-}$ pyrite	Decrease	Decrease
Sulfate reduction		
(5) $\text{SO}_4^{2-} + 2\text{CH}_2\text{O} + \text{H}^+ = 2\text{CO}_2 + \text{HS}^- + \text{H}_2\text{O}$	Increase	Increase
CaCO ₃ dissolution		
(6) $\text{CaCO}_3 + \text{CO}_2 + \text{H}_2\text{O} \rightleftharpoons \text{Ca}^{2+} + 2\text{HCO}_3^-$	Increase	No change

Source: Stumm and Morgan 1984.

Appendix table 2 Relative abundance categories of soil chemical variables in brackish water ponds

<i>Variable</i>	<i>1st decile (very low)</i>	<i>2nd-3rd decile (low)</i>	<i>4th-7th decile (medium)</i>	<i>8th-9th decile (high)</i>	<i>10th decile (very high)</i>
pH	< 4	4-6	6-8	8-9	> 9
Carbon (%)	< 0.5	0.5-1	1-2.5	2.5-4	> 4
Nitrogen (%)	< 0.15	0.15-0.25	0.25-0.4	0.4-0.5	> 0.5
Sulfur (%)	< 0.05	0.05-0.1	0.1-0.5	0.5-1.5	> 1.5
Phosphorus (mg l ⁻¹)	< 20	20-40	40-250	250-400	> 400
Calcium (mg l ⁻¹)	< 1,000	1,000-2,000	2,000-4,000	4,000-8,000	> 8,000
Magnesium (mg l ⁻¹)	< 700	700-1,500	1,500-3,000	3,000-4,000	> 4,000
Potassium (mg l ⁻¹)	< 100	100-400	400-1,200	1,200-1,700	> 1,700
Sodium (mg l ⁻¹)	< 2,500	2,500-7,000	7,000-15,000	15,000-25,000	> 25,000
Iron (mg l ⁻¹)	< 60	60-200	200-750	750-1,200	> 1,200
Manganese (mg l ⁻¹)	< 10	10-50	50-150	150-350	> 350
Zinc (mg l ⁻¹)	< 2	2-5	5-8	8-14	> 14
Copper (mg l ⁻¹)	< 1	1-2	2-8	8-11	> 11
Silicon (mg l ⁻¹)	< 30	30-100	100-500	500-750	> 750
Boron (mg l ⁻¹)	< 4	4-8	8-18	18-24	> 24
Cobalt (mg l ⁻¹)	< 0.5	0.5-1	1-2.5	2.5-3.5	> 3.5
Molybdenum (mg l ⁻¹)	< 0.3	0.3-0.5	0.5-0.9	0.9-1.2	> 1.2
Aluminum (mg l ⁻¹)	< 100	100-200	200-500	500-600	> 600
Barium (mg l ⁻¹)	< 0.5	0.5-1	1-1.5	1.5-3.5	> 3.5
Chromium (mg l ⁻¹)	< 1	1-2	2-4	4-7	> 7
Lead (mg l ⁻¹)	< 2	2-4	4-7	7-9	> 9

Note: Series of soil samples from 346 brackish water aquaculture ponds.

Source: Boyd and others 1994.

Appendix table 3 Relative abundance categories of soil chemical variables in freshwater ponds

<i>Variable</i>	<i>1st decile (very low)</i>	<i>2nd-3rd decile (low)</i>	<i>4th-7th decile (medium)</i>	<i>8th-9th decile (high)</i>	<i>10th decile (very high)</i>
pH	< 5	5-6	6-7	7-8	> 8
Carbon (%)	< 0.5	0.5-1	1-2	2-3.5	> 3.5
Nitrogen (%)	< 0.2	0.2-0.3	0.3-0.4	0.4-0.5	> 0.5
Sulfur (%)	< 0.01	0.01-0.025	0.025-0.05	0.05-0.125	> 0.125
Phosphorus (mg l ⁻¹)	< 5	5-10	10-20	20-40	> 40
Calcium (mg l ⁻¹)	< 600	601-1,200	1,200-3,400	3,400-7,600	> 7,600
Magnesium (mg l ⁻¹)	< 45	45-80	80-120	120-230	> 230
Potassium (mg l ⁻¹)	< 30	30-60	60-80	80-110	> 110
Sodium (mg l ⁻¹)	< 15	15-35	35-60	60-100	> 100
Iron (mg l ⁻¹)	< 10	10-50	50-130	130-210	> 210
Manganese (mg l ⁻¹)	< 5	5-20	20-40	40-75	> 75
Zinc (mg l ⁻¹)	< 0.2	0.2-1.5	1.5-2.5	2.5-5	> 5
Copper (mg l ⁻¹)	< 0.3	0.3-1.25	1.25-2.5	2.5-6	> 6
Silicon (mg l ⁻¹)	< 20	20-40	40-60	60-100	> 100
Boron (mg l ⁻¹)	< 0.3	0.3-0.5	0.5-0.75	0.75-1.25	> 1.25
Cobalt (mg l ⁻¹)	< 0.1	0.1-0.2	0.2-0.35	0.35-0.8	> 0.8
Molybdenum (mg l ⁻¹)	< 0.1	0.11-0.15	0.15-0.2	0.21-0.35	> 0.35
Aluminum (mg l ⁻¹)	< 3.5	3.5-75	75-120	120-200	> 200
Barium (mg l ⁻¹)	< 0.5	0.5-1	1-1.5	1.5-4	> 4
Chromium (mg l ⁻¹)	< 0.5	0.5-0.75	0.75-1	1-1.75	> 1.75
Lead (mg l ⁻¹)	< 1	1-1.25	1.25-1.5	1.5-2.5	> 2.5

Note: Series of soil samples from 358 freshwater aquaculture ponds.

Source: Boyd and others 1994.

Appendix table 4 Selected biomarkers proposed in study of environmental and/or toxicological responses in fish

<i>Type</i>	<i>Biomarker</i>	<i>Comments</i>
DNA alterations	DNA adducts	Specific for genotoxic chemicals
DNA alterations	Strand breaks in DNA	Specific for genotoxic chemicals
DNA alterations	Hypomethylation of DNA	Specific for genotoxic chemicals
DNA alterations	Cytogenetic effects	Specific for genotoxic chemicals
Biochemical	Induction of Cyt. P-450	Organic planar compounds
Biochemical	Metallothioneins	Selected metals
Biochemical	ATPases	Nonspecific
Biochemical	Aminolevulinic acid dehyd.	Specific for lead
Biochemical	Methemoglobin	Specific for nitrite and other chemicals
Biochemical	Acetylcholinesterase	Specific for organophosphorous and carbamates
Physiological	Adenylate energy change	Nonspecific
Physiological	Glycogen	Nonspecific
Physiological	Scope for growth	Nonspecific
Physiological	Corticosteroids/catecholamines	Nonspecific-primary stress response
Physiological	Plasma thyroid hormone	Developmental alterations in growth
Physiological	Growth hormone	Growth inhibitors: chlorpyrifos and phenol
Physiological	Stress (heat shock) proteins	Nonspecific
Immunological	Leucokrit	General screen assay
Immunological	Macrophage phagocytosis	
Immunological	Macrophage pinocytosis	
Immunological	Native immunoglobulin	Humoral comprehensive assay
Immunological	Specific antibody quantitation	Humoral host resistance challenge assay
Immunological	Increase disease susceptibility	Comprehensive host resistance challenge assay
Histopathological	Hepatic biomarkers	Different lesions depending on the chemical
Histopathological	Vertebral abnormalities	Temperature, oxygen, metals

Source: Tarazona and Munoz 1995.

Appendix table 5 Provisional tolerable weekly intake for selected elements

<i>Element</i>	<i>Unit per kg of body weight</i>	<i>Comment</i>	<i>Source</i>
Aluminum	7 mg		WHO (1989b)
Arsenic (inorganic)	0.015 mg	Narrow margin between PTWI and levels that have toxic effects.	WHO (1989b)
Cadmium	7 g	Highly dependent on rates of consumption of contaminated food products. ^a	WHO (1989b)
Copper	3.5 mg		WHO (1982)
Iron	5.6 mg		WHO (1983)
Lead	25 g		WHO (1993)
Mercury (total)	5 g		WHO (1989b)
Methyl mercury	3.3 g		WHO (1989b)
Tin (inorganic)	14 mg	No PTWI set for organotin compounds.	WHO (1989b)
Zinc	7 mg		WHO (1982)
PCBs	0.28 mg	No-effect level in monkeys.	WHO (1990)

a. Considerable portions of many populations ingest more Cd than the limit so one might argue for the avoidance of any fish product containing excessive Cd (Phillips 1993, 304).

Appendix table 6 Import standards for contaminant residues in fish and shellfish

Contaminant	Median standard		Range of standards ¹	United States import standard		Canadian import standard		Japanese import standard		European Union import standard	
	Shellfish ¹	Fish ¹		Shellfish ²	Fish ²	Shellfish ³	Fish ³	Shellfish ⁴	Fish ⁴	Shellfish ^{5,21,23*}	Fish ^{5,21*}
Arsenic (AS)		1.5	0.1-5.0	76 ⁶		3.5 ²⁹	3.5 ²⁹			**17,18,20	**18,20
Cadmium (Cd)	1	0.3	0.05-2.0	3 ⁶						**17,18,20	**18,20
Chromium (Cr)	1	1	1	12 ⁶						**17,18,20	**18,20
Copper (Cu)	20	20	10-100							**17,18,20	**18,20
Lead (Pb)	2	2	0.5-10	1.5 ⁶		0.5 ²⁹	0.5 ²⁹			**17,18,20	**18,20
Mercury (Hg)	0.5	0.5	0.1-1.0	1.0 ^{7,8}	1.0 ^{7,8}			0.4,0.3 ^{25,26}	0.4,0.3 ^{25,26}	0.5 ^{8,13,15,18,20}	0.5,1.0 ^{8,13,14,15,18,20}
Nickel (Ni)				70 ⁶						**17,18,20	**18,20
Selenium (Se)	0.3	2	0.3-2.0							**17,18,20	**18,20
Tin (Sn)	190	150	50-250							**17,18,20	**18,20
Zinc (Zn)	70	45	40-100							**17,18,20	**18,20
Paralytic shellfish poison (PSP)						0.8 ⁸		4.0 MU/g ^{8,27}		0.8 ¹⁶	
Neurotoxic shellfish poison (NSP)											
Diarrhetic shellfish poison (DSP)								0.05 MU/g ^{5,27}		**16,22	
Dyes										**18	**18
Petroleum hydrocarbons										**17	
Organophosphorus compounds										**18	**18
Organohalogenated compounds										**17,18,19	**18,19
PCBs				2.0 ⁸	2.0 ⁸			0.5,3.0 ^{8,24}	0.5,3.0 ^{8,24}	**18,19	**18,19
2,3,7,8 - TCDD							0.02 ppb ³²				
DDT and derivatives				5.0 ⁸	5.0 ⁸						
Dieldrin				0.3 ^{8,12}	0.3 ^{8,9,12}			0.1 ²⁸			
Chordane				0.3 ⁸	0.3 ⁸						
Chlordecone				0.3,0.4 ^{8,10}	0.3 ⁸						
Heptachlor/Heptachlor Epoxide				0.3 ⁸	0.3 ⁸						
2, 4-D				1.0	1.0						
Mirex				0.1 ⁸	0.1 ⁸						
Diquat				0.1	0.1						
Fluridone				0.5 ¹¹	0.5 ⁹						
Glyphosate				3.0	0.25 ⁹						
Simazine					12 ⁹						

(Table continues on next page.)

Appendix table 6 (continued)

* Limits are in mg l⁻¹ unless otherwise specified. In the case of contaminant residues in fish, mg l⁻¹ is mg (of contaminant) per kg of fish weight.

1. Median international standards and their ranges adapted by Pullen *et al.*, 1993 from Nauen, 1983.
2. USFDA and EPA tolerances, action levels and guidance levels relating to safety attributes of fish and fishery products. In many cases, these levels represent the point at or above which the agency will take legal action to remove products from the market (Fish and Fishery Products Hazards and Controls Guide, USFDA, January 1998).
3. Bureau of Food Regulatory, International and Interagency Affairs, Health Protection Branch, Health Canada.
4. Specifications and Standards for Foods, Food Additives, under the Food Sanitation Law, JETRO, 1996.
5. Based on EU Directives 91/492/EEC, 91/493/EEC, 96/325/EC, 79/923/EEC and Commission Decision 93/351/EEC.
6. For crustacea only.
7. Methylated mercury.
8. Specifies edible portion.
9. Fin fish only.
10. 0.4 mg l⁻¹ for crabmeat and 0.3 mg l⁻¹ for all other fish.
11. Crayfish only.
12. Includes dieldrin and aldrin.
13. Contaminant concentration should be measured per fresh weight of the fish.
14. All fish have a standard of 0.5 mg l⁻¹ except the following which have a 1.0 mg l⁻¹ standards: Sharks (all species), Tuna (*Thunnus* spp.), Little tuna (*Euthynnus* spp.), Bonito (*Sarda* spp.), Plain bonito (*Orcynopsis unicolor*), Swordfish (*Xiphias gladius*), Sailfish (*Istiophorus platypterus*), Marlin (*Makaira* spp), Eel (*Anguilla* spp.), Bass (*Dicentrarchus labrax*), Sturgeon (*Acipenser* spp.), Halibut (*Hippoglossus hippoglossus*), Redfish (*Sebastes marinus*, *S. mentella*), Blue ling (*Molva dipterygia*), Atlantic catfish (*Anarhichas lupus*), Pike (*Esox lucius*), Portuguese dogfish (*Centroscymnus coelolepis*), Rays (*Raja* spp.), Scabbardfishes (*Lepidopus caudatus*, *Aphanopus carbo*), Anglerfish (*Lophius* spp.) Commission Decision 93/351/EEC.
15. Total mercury.
16. For live bivalve mollusks only (Council Directive, 91/492/EEC).
17. The standards for these chemicals for live bivalve mollusks have yet to be established, however they have been specified as parameters that will be regulated in live bivalve mollusks based on the permissible daily intake for each chemical and any deleterious effects on taste (Council Directive 91/492/EEC).
18. Countries exporting to the EU must submit a plan to monitor in these chemicals and their metabolites in live aquaculture animals, their excrement, body fluids and all places the animals are bred or kept. Plans to monitor the aquaculture products must also be submitted (Council Directive 96/325/EC).
19. Monitoring requirement referred to in above note 18 specifies that Aorganochlorine compounds (including PCBs)A be monitored.
20. Monitoring requirement referred to in above note 18 specified that Achemical elements@ be monitored.
21. The EU has not set standards for many contaminants however national laws may apply.
22. The standard specifies that the customary biological testing methods must not give a positive result for the presence of DSP in the edible parts of the mollusk.
23. A country exporting to the EU must identify production areas from which live bivalve mollusks may be harvested for exportation to the EU. Monitoring of these areas for microbiological and environmental contamination and the presence of biotoxins is an important consideration in granting approval for a country to export live bivalve mollusks to the EU (Council Directive 91/492/EEC).
24. The PCB standard specifies 0.5 mg l⁻¹ for fishes and shellfishes from the ocean and open sea and 3.0 mg l⁻¹ for fishes and shellfishes from inland seas and bays.
25. The mercury standard specifies 0.4 mg l⁻¹ for total mercury and 0.3 mg l⁻¹ for methyl mercury (as mercury).
26. The mercury standard does not apply to tuna fishes (tuna, swordfish, bonito), fishes and shellfishes from inland rivers and fishes and shellfishes from the deep sea (rockfishes, *Bdrys splendens*, gindara, benizuwaigani, ecchubaigai and sharks).
27. One MU (mouse unit) represents the amount of toxin that kills a mouse of 20 g in 15 minutes.
28. Applies to hard shell mussels only.
29. In fish protein.
30. Swordfish and shark are exempted from the mercury guideline.
31. For clams, oysters and mussels only.
32. Ppb equals parts per billion or micrograms of contaminant per kilogram of fish weight.

Appendix table 7 Import bacteriological standards for fish and shellfish

Contaminant	United States import standard		Canadian import standard		Japanese import standard		European Union import standard	
	Shellfish ^{1*}	Fish ^{1*}	Shellfish ^{2*}	Fish ^{2*}	Shellfish ^{3*}	Fish ^{3*}	Shellfish ^{4*}	Fish ^{4*}
Bacteria count								
E. coli spp.	230/100 MPN/g ^{12,31}		40 CFU/g ¹³	40 CFU/g ¹³	50,000, 100,000/g ¹⁷ 230/100g ¹⁸	100,000/g ¹⁷	100 CFU/g ^{22,23,26}	230 MPN/100g ^{29,30}
Enterotoxigenic E. Coli	1x10 ³ ETEC/g ^{5,32}	1x10 ³ ETEC/g ^{5,32}						
Coliform group					presence of organism ¹⁹	presence of organism ¹⁹		
Fecal coliform	330/100 g ^{12,31}						330 MPN/100g ^{29,30}	
Staphylococcus spp.	10 ⁴ MPN/g or presence of toxin ^{8,31}	10 ⁴ MPN/g or presence of toxin ^{8,31}	10,000 CFU/g ¹⁴	10,000 CFU/g ¹⁴	1,000 CFU/g ^{22,23,24}			
Salmonella spp.	presence of organism	presence of organism	presence of organism ¹⁵	presence of organism ¹⁵			presence of organism ^{20,21,31}	
Listeria spp.	presence of organism ^{5,6}	presence of organism ^{5,6}	100 CFU/g ¹⁶	100 CFU/g ¹⁶				
Clostridium spp.	presence of organism or toxin ⁷	presence of organism or toxin ⁷						
Vibrio cholerae	presence of organism ^{5,9}	presence of organism ^{5,9}						
Vibrio parahaemolyticus	10 ⁴ /g ^{5,10}	10 ⁴ /g ^{5,10}						
Vibrio vulnificus	presence of organism ^{5,11}	presence of organism ^{5,11}						
Thermotolerant bacteria							100 CFU/g ^{22,23,25}	
Mesophilic aerobic bacteria							100,000, 500,000, 1,000,000 CFU/g ^{22,23,27}	

* Limits are in mg l⁻¹ unless otherwise noted.

1. USFDA and EPA tolerances, action levels, and guidance levels relating to safety attributes of fish and fishery products. In many cases these levels represent the point at or above which the agency will take legal action to remove products from the market (Fish and Fishery Products Hazards and Controls Guide, USFDA, January 1998).

2. Bureau of Food Regulatory, International and Interagency Affairs, Health Protection Branch, Health Canada.

(Table continues on next page.)

Appendix table 7 (continued)

3. Specifications and Standards for Foods, Food Additives, under the Food Sanitation Law, JETRO, 1996.
4. Based on EU Directives 91/492/EEC, 91/493/EEC, 96/325/EC, 79/923/EEC and Commission Decision 93/351/EEC.
5. For ready to eat fishery products (minimal cooking by consumer).
6. Specifies presence of *Listeria monocytogenes*.
7. For *Clostridium Botulinum*, specifies either (a) presence of viable spores or vegetative cells in products that will support their growth or (b) presence of the toxin.
8. Specifies either (a) positive for staphylococcal enterotoxin or (b) *Staphylococcus aureus* level is equal to or greater than 104/g (MPN).
9. Presence of toxigenic 01 or non-01.
10. Specifies 10⁴/g (Kanagawa positive or negative).
11. Specifies presence of pathogenic organism showing.
12. For clams and oysters, fresh or frozen, guideline specifications (a). *E coli* MPN of 230/100g (average of subsamples or 3 or more of 5 subsamples); (b) APC- 500,000/g (average of subsamples or 3 or more of 5 subsamples).
13. For cooked fish: out of five sample units 1 sample can be >4 CFU/g but none can be over 40 CFU/g. For all fish except cooked: out of two sample units 1 sample can be >4 CFU/g but sample units 1 sample can be >4 CFU/g but none can be greater than 40 CFU/g.
14. Out of five sample units, 1 can be greater than 1,000 CFU/g and none can be greater than 10,000 CFU/g.
15. Out of five 50-g samples, no *Salmonella* can be present.
16. Out of five samples none can exceed 100 CFU/g.
17. For raw consumption oysters the standard is 50,000/g. For frozen fresh fish and shellfish for raw consumption the standard is 100,000/g.
18. For raw consumption oysters.
19. For frozen fresh fish and shellfish for raw consumption.
20. For cooked crustaceans and cooked molluscan shellfish.
21. For shelled and shucked products: out of 5 samples, 25 g samples no *Salmonella* can be present. For live bivalve mollusks: a 25 g sample of mollusk flesh must not contain *Salmonella*. Bacterial counts should be determined using the MPN method (see note 31).
22. For shelled and shucked products.
23. The criteria for these EU standards is specified by four variables: M, m, n, c, the values of which are listed in the footnotes of the particular standards. The variable n refers to the number of fish or shellfish samples to be tested. For all the criteria listed here n=5 and therefore is recommended that 5 samples be tested. If 5 samples are not tested, n would have to be changed accordingly. The other variables are used to specify the criteria as follows: the samples tested (# samples = n) are considered (a) satisfactory if all the values are 3 m or less; (b) acceptable if the values observed are between 3m and M and c/n is 2/5 or less. The quality of the samples is considered unsatisfactory if any of the values are above M or if c/n is greater than 2/5.
24. Specifies for *Staphylococcus aureus*. M=1000, m=100, n=5, c=2 (refer to note 23).
25. Specifies growth should be done at a temperature of 44.5 C on solid medium. M=100, m=10, n=5, c=2 (refer to note 23).
26. Specifies growth on solid medium. M=100, m=10, n=5, c=1 (refer to note 23).
27. Specifies growth should be at a temperature of 30.5 C. For whole products M=100000, m=10000, n=5, c=2; For shelled or shucked products with the exception of crabmeat, M=500000, m=50000, n=5, c=2. For crabmeat M=1,000,000, m=100,000, n=5, c=2 (refer to note 23).
28. Are guidelines to help manufacturers decide whether their plants are operating satisfactorily and to assist them in implementing the production monitoring procedures.
29. For live bivalve mollusks.
30. The standard specifies that the sample must contain , fecal coliforms or less than 230 *E.Coli* per 100 g based on five tube, three dilution MPN test or test with equivalent accuracy.
31. Determined by most probable number (MPN). See Glossary. (APHA, 1995)
32. Specifies Enterotoxigenic *E. Coli* (ETEC) 1 x 10³/g, LT or ST positive.
33. Determined by colony forming units (CFU). See Glossary. (APHA, 1995).

Notes

1. Bromage and Shepherd 1974; Pillay 1990; EU 1979.

2. Functionally alkalinity is the amount of a strong acid necessary to titrate a water to the equivalence point of atmospheric CO₂ which occurs at about a pH of 4.5. Because the pH of 4.5 is approximately the limit at which fish and shellfish can survive, alkalinity is a good measure of the ability of the water to prevent reductions in pH to the level at which the fish undergo extreme disturbance. Adapted from Stumm and Morgan 1981, 185.

3. Alkalinity can be represented as $[\text{Alk}] = [\text{HCO}_3^-] + 2[\text{CO}_3^{2-}] + [\text{OH}^-] - [\text{H}^+] + C_b - C_a$ where C_b represents the total equivalents of bases other than the carbonate and hydroxide species. This can include species such as ammonium, borates, silicates and phosphates. C_a represents the total equivalent concentration of acids other than the hydrogen ion. Note that because the hydrogen ion contributes to alkalinity, a change in pH can result in a change in alkalinity.

4. Production of an acid by a metabolic process neutralizes some of the bases, reducing the acid neutralizing capacity of the water and thus decreasing alkalinity. The production of a base results in an increase in the acid neutralizing capacity of the water and thus an increase in alkalinity. This also applies to H⁺ and OH⁻. Because H⁺ is an acid and OH⁻ is a base, a reduction in pH (a decrease in OH⁻ and an increase in H⁺) will result in a reduction in alkalinity and vice versa.

5. In aquaculture low pH is often a result of sulfuric acid formation by the oxidation of sulfide-containing bottom soils. This occurs most commonly where iron pyrite is present (Lawson, 1995, 26). High pH in aquaculture is commonly a result of excess photoplankton photosynthesis in waters with high alkalinity and low calcium hardness.

6. Boyd 1990, 143; Lawson 1995, 25.

7. Romaine 1985 as cited in Lawson 1995, 25.

8. For more information on aeration see Lawson (1995).

9. BOD is often measured as the five day BOD (BOD₅ in mg/l) which is defined as the amount of dissolved oxygen used up by microorganisms in the biochemical oxidation of organic matter over a 5 day period at 20°C. (Metcalf and Eddy, Inc. 1991, 71.) BOD for aquaculture operations can also be measured using a shorter period of time than 5 days and a temperature equivalent to that of the pond. The result is expressed as a function of time ($\text{mg l}^{-1} \text{hr}^{-1}$). (Boyd 1981, p130.) COD which represents the amount of organic matter that can be chemically oxidized in a given water is also commonly used because of the ease of its measurement. BOD can be estimated from COD in using the following correlation developed for channel catfish ponds: $\text{BOD} (\text{mg l}^{-1} \text{hr}^{-1}) = -1.006 - 0.00148\text{C} - 0.0000125\text{C}^2 + 0.0766\text{T} + 0.000253\text{CT}$; $\text{C} = \text{COD mg/l}$ $\text{T} = \text{temp } (^\circ\text{C})$. Boyd and others 1978 as cited in Boyd 1981, 130.

10. Svobodová and others 1993, 9. A maximum COD concentration of 20–30 mg/l is also recommended.

11. Ammonia is also a waste product excreted by fish and shellfish, and hence ammonia will be produced during an aquaculture operation.

12. For more information on these methods, see Metcalf and Eddy, Inc. 1991.

13. EIFAC 1984, 8; Lawson 1995, 34; Boyd 1990, 161.

14. For more information, see Metcalf and Eddy, Inc. 1991.

15. Peavy and others 1985. For detailed design, see Metcalf and Eddy, Inc. 1991.

16. Tucker and Robinson 1990; Swann 1993, 2.

17. Huguenin and Colt 1989; Svobodová and others 1993, 24.

18. Smith and others 1976; Lawson 1995, 35.

19. Boyd 1990, 185-187. For more information on soils and sediments in aquaculture, see Boyd 1995.
20. Boyd 1995, 49. Specifies a pH of less than 3.5 in a 1:1 mixture of soil and distilled water.
21. Boyd 1995, 272. Field identification of potential acid sulfate soils can be made by mixing a few grams of fresh soil with a few milliliters of fresh, 10–30% hydrogen peroxide. If pyrite is present there will be a rigorous reaction with the production of bubbles. This followed by measurement of a pH of less than 3 for the hydrogen peroxide solution is confirmation of a potential acid-sulfate soil.
22. Boyd 1995, 276.
23. Shazili 1995; Eisler 1971; Sunda 1978.
24. Salomons and Förstner 1984; Malm and others 1990, 12.
25. Mance 1987.
26. For more information see Cunningham and Tripp 1973 or Sayler and others 1975.
27. WHO 1973, cited in Dojlido and Best 1993, 85.
28. UNEP 1985, 13.
29. Rosenthal, personal communication.
30. UNEP 1985, 10.
31. Pillay 1992, 102; Phillips 1993, 305.
32. Phillips 1993, 304–5; Furness and Rainbow 1990, 150.
33. Mantoura and others 1978; Dojlido and Best 1993, 65–6.
34. USEPA 1993; Piper and others 1982; Meade 1989.
35. Nordstrom 1982, cited in Dojlido and Best 1993, 101.
36. Hermann 1987, cited in Dojlido and Best 1993, 102.
37. Phillips 1993, 300.
38. Mance 1987, cited in Dojlido and Best 1993, 177.
39. Mance 1987, cited in Dojlido and Best 1993, 177.
40. Nriagu 1980, cited in Dojlido and Best 1993, 201.
41. Mance 1987, cited in Dojlido and Best 1993, 202.
42. EIFAC 1984, 15.
43. Mance 1987, cited in Dojlido and Best 1993, 70.
44. Dojlido and Best 1993, 107; Stumm and Morgan 1981, 372.
45. Liebman 1958, cited in Dojlido and Best 1993, 107.
46. Zabel and others 1988, cited in Dojlido and Best 1993, 107.
47. Wilson 1976, cited in Dojlido and Best 1993, 80.
48. Piper and others 1982; USEPA 1993.
49. Dojlido and Best 1993, 145; Moore and Ramamoorthy 1984.
50. Dojlido and Best 1993, 147; Moore and Ramamoorthy 1984.
51. Dojlido and Best 1993, 147; Furness and Rainbow 1990, 119.
52. Phillips 1993, 305; WHO 1983, 29; Pillay 1992, 102.
53. Dojlido and Best 1993, 172; Förstner and Wittman 1981.
54. Phillips 1993, 306; Furness and Rainbow 1990, 119.
55. Dojlido and Best 1993, 184.
56. USEPA 1993; EU 1979; Meade 1989.
57. Boyd 1990, 387; Boyd 1996; Boyd 1979, 187.
58. Dojlido and Best 1993, 209; Svobodová and others 1993, 21.
59. Svobodová and others 1993, 22; USEPA 1993.
60. Brune and Tomasso 1991, 137; Svobodová 1993, 27–28.
61. Not all instances of off-flavor are caused by water quality problems. Off-flavor may also result from post-mortem oxidation of fats due to prolonged or improper storage, or from certain feed ingredients such as those high in marine fish oil. However, if source water has an unusual odor or if the presence of compounds which might cause off-flavor is suspected, off-flavor should be tested for.
62. For more information on pesticides see Macrae and others 1993, 3521–41.
63. Manahan 1991, 522; USGPO 1987.
64. Rosenthal, personal communication. For more information, contact the International Council for the Exploration of the Sea, which is conducting research on biologically active complexes.
65. Svobodová 1993, 28.
66. Lloyd 1992, 59. See also MAFF 1989; Svobodová 1993, 28; Pillay 1992, 102.
67. Bailey and others 1978, cited in Dojlido and Best 1993, 285.
68. USEPA 1993; Svobodová 1993, 29.
69. Lobel and others 1994, 3–4. See also, Kleeman and others 1988.
70. Phillips 1993, 302; Dojlido and Best 1993, 287.
71. WHO 1989a, 43; Mara and Cairncross 1989, 89, 116.
72. Pillay 1992, 52; WHO 1989a, 43; Mara and Cairncross 1989, 89. For maps of areas of endemism see Mara and Cairncross 1989, 85–87. For treatment procedures see Mara and Cairncross 1989, 112–113.
73. USDHH, USPHS, USFDA 1995, c-9.
74. WHO 1989, 44–48; Shereif and Mancy 1995.
75. Pillay 1992, 71, 105. Other common species include toxic marine dinoflagellates (*Ptychodiscus* and *Gonyaulax*), some blue-green algae (*Microcystis aeruginosa*), and the brackish water chrysophyte (*Prymnesium parvum*). Boyd 1990, 163.
76. Other methods employing temperature and salinity stress and chlorination have not been very successful. Ozonation has met with limited success, but there is controversy over its usefulness. Pillay 1992, 106.

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Species Index

- Aeromonas*, 40
Arthropods, 25
Atlantic salmon, 8
- Bass, 8, 24, 60
Brackishwater prawn, 10
Brine shrimp, 8
Brook trout, 8
Brown shrimp, 8
- C. commercialis*, 26
Carp, 14, 20
Catfish, 41, 56, 57, 61
Channel catfish, 8, 10, 13, 14, 16, 20
Chanos chanos, 18
Chinook salmon, 8
Clams, 26, 31, 41
Clonorchis sinensis, 40
Clostridium botulinum, 40
Cockles, 26
Coho salmon, 8, 39
Cold water fish, 14
Common carp, 8
Crab, 26
Crassostrea gigas, 26
Cyclops abyssorum, 24
Cyprinid, 15, 20, 27, 30
- E. coli*, 40
Eel, 14
Escherichiae, 40
European eel, 8
- Fasciolopsis buski*, 40
Freshwater crayfish, 13
Freshwater crustaceans, 13
Freshwater prawn, 8, 10
- Grass carp, 10, 58
Guppy, 39
Hatchling silver carp, 13
- Japanese eel, 8
- Klebsiellae*, 40
- M. rosenbergii*, 10
Marine fish, 10, 14, 18
mollusks, 25, 26, 27, 28, 30, 31
Mullet, 8
mussels, 27, 28, 39, 42
Mytilus edulis, 28
- Ostrea edulis*, 32
Oyster, 24, 26, 27, 30, 32, 38, 41, 42, 57, 60
- P. monodon*, 18, 19, 22
P. vannamei, 8, 10, 14, 18, 19, 20
Pacific Oyster, 26
Penaeid shrimp, 14, 18
Penaeus japonicus, 26
Penaeus monodon, 21, 57
Pike, 24, 39
Pink Shrimp, 8
Plaice, 8

Pseudomonas, 40
Pyrodinium bahamense var. *compressa*, 42

Quahog, 42

Rainbow trout, 8, 29, 30, 39, 59
Red hybrid tilapia, 10
Red swamp crawfish, 8, 14

Salmonella, 40
Salmonid, 8, 11, 12, 14, 18, 19, 27, 28, 29, 30,
32, 60
Schistosoma japonicum, 40
Shark, 24

Sockeye salmon, 8
Sole, 8
Streptococcus, 40
Striped bass, 8
Swordfish, 24

Tilapia, 8, 10, 14, 24, 57, 60
Trout, 10, 13, 14, 16, 20, 60
Tuna, 24
Turbot, 8

Walleye, 24
Warm water crustaceans, 14
Warm water fish, 14



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