

9.4 Aquaculture and human consumers of aquatic foods

9.4.1 Introduction

This environmental value includes aquaculture as well as human consumers of aquatic foods. The Chapter marks the first occasion in which joint guidelines have been provided for the protection of aquaculture in Australia and New Zealand. These guidelines, which are mostly based on value judgements for acceptable risks, are for influent water quality only. Effluent water quality is not considered in these guidelines as it is dealt with through State and Federal Government legislation and regulations in Australia and through the Resource Management Act and Industry Agreed Implementation Standards in New Zealand.

It is generally agreed that good quality water is the most important input for aquaculture and thus a key element in the success of all phases of culture operations, including hatchery, nursery, growout and holding or transport of live product to market. Poor water quality can adversely effect the development and growth of cultured aquatic organisms and even result in death. As noted by Zweig et al. (1999), it may also degrade the quality of the product by tainting the flavour or by causing accumulation of high enough concentrations of toxic substances to endanger human health.

Some of the guidelines presented here should be used with some caution as they are not based on a critical assessment of a wide data set. Rather they are based on the personal experience of a number of industry specialists (noted as ‘pers comm’ in the tables; the sources are listed in Appendix 9.1) or are taken from recommendations of ‘safe’ levels in technical and scientific literature (a discussion of the confidence levels is provided in Section 9.4.1.5).

The Chapter focuses mostly on cultured species of finfish, molluscs and crustaceans, although as detailed in Section 9.4.1.1, a wide range of other aquatic species are cultured including plants, reptiles and invertebrates. The report is in two main parts, the first deals with the growth and survival of culture species, the second deals with residues and contaminants in products for human consumption.

Water quality guidelines are provided in Section 9.4.2 for optimising growth and survival of aquaculture species. These are divided into:

- physico-chemical stressors
- inorganic toxicants
- organic toxicants
- pathogens and biological contaminants

Section 9.4.3 discusses the issues of, and provides guidelines for, the safety for human consumers of aquatic foods. It must be noted that these aquatic foods for human consumption can be sourced through aquaculture as well as recreational (including indigenous fishing) and commercial fisheries. The main difference is that aquaculture products are usually harvested from a partly controlled or carefully selected environments, whereas recreational and commercial fisheries are based upon wild populations of fish, crustacean and mollusc species, which are supported by natural habitats and food webs. Thus to protect wild stocks

of aquatic organisms, it is recommended that the water quality guidelines for the protection and maintenance of aquatic ecosystems (Chapter 3 of Volume 1, and Volume 2) be applied.

As discussed in Section 2.1.3 (Volume 1), the different environmental values are interdependent and the uses within each can have impacts on others. For example, agricultural runoff can often contain contaminants which adversely affect downstream aquaculture or fisheries. Conversely, aquacultural activities can affect environmental values downstream.

A check of the recommendations provided for ecosystem protection often will see lower guidelines than those provided for protection of aquaculture species (Section 9.4.2). The main reason is that the aquaculture species are held in a specific water environment for shorter periods of time, usually less than 12 months, than those wild species which can spend all of their life in the one water body. In fact, the various life cycle stages of aquaculture species may be held in totally separate culture environments (e.g. where the hatchery, nursery and growout facilities are in different locations and changes of water are undertaken regularly). As indicated above, control or selection of the environment is undertaken to reduce risks to the health and survival of the culture species. Furthermore, the cultured organisms are often fed artificial (formulated) or selected diets, reducing the potential for exposure from contaminants in the natural environment. However, these formulated diets could include contaminated ingredients, and so the sources of all constituents of the feeds need to be identified and checked to prevent possible adverse effects of the culture species.

A range of chemicals and therapeutants are used in aquaculture operations for the control of a variety of pathological conditions in the culture organisms. Many therapeutants are administered on veterinary advice, and provided they are used under the appropriate instructions, should not cause problems. Therefore, they are not included in this report, except for brief notes in Section 9.4.3.1. In Australian and New Zealand aquaculture the level of use of the chemicals is much lower than that found in other primary industries, and certainly much lower than the levels of use in overseas aquaculture operations. However, their use can create potential problems; for example, formaldehyde (formalin) is commonly used by prawn farmers to control algal blooms and reduce gill fouling in concentrations that could be toxic to prawns and humans (Burford, pers comm). Some of these potential contaminants are not included in this report, however, a process of registration is being undertaken by the National Registration Authority (NRA). Readers are advised to consult the NRA web site (www.dpie.gov.au/NRA/index.html).

9.4.1.1 Aquaculture in Australia and New Zealand

Aquaculture involves the production of food (plant and animal food) for human consumption, fry for recreational fishing and natural fisheries, ornamental fish and plants for the aquarium trade, raw materials for energy and biochemicals (algal extracts and pigments), and a number of items for the fashion industry (shell buttons, pearls and fish and crocodile skins).

With wild fisheries approaching maximum sustainable levels and many already being over exploited, aquaculture is increasingly important worldwide as a source of aquatic food and other products.

For the financial year 1997/98, almost 30 700 tonnes of product and around 9.3 million juveniles (mostly finfish fry and ornamental fish), were produced at an estimated farm gate value in excess of \$517.4 million (O'Sullivan & Roberts 1999). This represents approximately 25% of total aquatic food production in Australia.

During 1997/98 over 60 species were cultured on a commercial scale, with several other species undergoing pilot or experimental production. The main commercial species included salmonids (5 species), southern bluefin tuna, barramundi, native freshwater fish (at least 10 species), introduced freshwater finfish (2 species), marine fish (at least 4 species), aquarium fish (many species), eels (2 species), freshwater crayfish (3 species), Penaeid prawns (2 species), brine shrimp, mud crabs, freshwater shrimp, freshwater prawns, edible oysters (at least 5 species), pearl oysters (at least 3 species), blue mussels, freshwater mussels, scallops, clams (2 species), abalone (2 main species), trochus (1 species), microalgae (1 species), crocodiles (2 species) and polychaete worms (2 species).

In order of value, the most important sectors were pearl oysters (\$229.4 million), southern bluefin tuna (\$87.2 million), salmonids (\$82.7 million), edible oysters (\$47.9 million) and prawns (\$35.4 million). Together these sectors contribute over 90% of total value of production.

Other valuable species included barramundi (\$7.0 million), freshwater crayfish (\$4.9 million), mussels (\$4.1 million), native freshwater fish (\$3.9 million), microalgae (\$3.0 million), crocodiles (\$3.0 million), aquarium fish (\$2.8 million), eels (\$2.3 million), scallops (\$1.2 million), abalone (\$1.1 million) brine shrimp (\$0.9 million), and aquatic worms (\$0.3 million). Other species beginning to move from research to pilot-scale production include marine fish, crabs, freshwater shrimp, and freshwater mussels.

Since 1988/89, there has been almost a 160% increase in the tonnes produced and a 280% increase in the value of this production. It is likely that a moderate rate of increase (10%+) will continue for another few years providing access to sites and venture capital is not limited.

In New Zealand, the main culture species are green shell mussels, Pacific salmon and Pacific oysters. According to data provided by the New Zealand Fishing Industry in 1998 (Maddock pers comm. 1999), annual production of these species was, respectively, approximately 33 203 tonnes (worth NZ\$118.2 million), 3841.7 tonnes (NZ\$32.1 million) and 1 0342.5 tonnes (NZ\$11.5 million). This represents an increase of 6 300 tonnes and a value of NZ\$37 million over the previous year. The annual increase in value for the current year is estimated to be approximately 30%. Aquaculture now contributes to over 13% of all New Zealand aquatic food exports (little production is consumed domestically).

A range of other species are being cultured in New Zealand including rock lobsters, scallops, seaweeds, sponges, freshwater shrimp, flatfish and paua (abalone).

9.4.1.2 Relationship between water quality, aquaculture production and human food safety

Aquatic organisms are in such intimate association with their water environment that their performance is strongly influenced by water quality parameters. Schreck and Li (1991) noted that any environmental factor that has a level of toxicity can cause a stress response and reduce the capacity of the cultured organism to grow, resist disease or reproduce.

Aquaculture is often heralded as the 'farming of the seas', however, there are several important differences between terrestrial and aquatic farming. Most importantly, aquatic animals maintain a high rate of respiration since less oxygen is present in a given volume of water than in an equal volume of air. This high respiration rate, coupled with a large presence of dissolved substances in water, provides the basis for a greater potential for aquatic organisms to be exposed to toxic substances (Brune & Tomasso 1991).

There is a strong relationship between water quality and product performance. To produce finfish, crustaceans, molluscs and other aquatic animals and plants successfully and efficiently, maintaining the water quality to suit the environmental requirements of the particular culture species is of paramount importance. Appropriate culture conditions, which include optimal water quality, mean:

- good growth, reproduction and survival;
- higher production and market value, reduced costs;
- improved profits.

A number of different production systems are utilised in the aquaculture industry. However, all product containment methods can be placed in any one of three groups based on how the water is sourced:

- in or on the water source (e.g. cages, long lines, racks, bottom culture);
- water is extracted from the source and, via a flow through system, is returned to the water source at a point other than the supply point (e.g. ponds, raceways, tanks);
- water is extracted from the source and then recirculated with treatment so that the water quality is optimised (e.g. tanks, ponds).

Water quality in aquaculture encompasses all the physical, chemical and biological parameters that affect aquaculture production. Appropriate site selection is a key factor in managing many physical and some chemical factors.

Apart from correct site selection, farm management procedures are aimed at improving the biological and in some instances the physical and chemical conditions of the aquaculture water (e.g. through aeration in ponds or tanks).

Aquaculturists have a strong commercial interest in maintaining as close to optimal water quality conditions as possible. However, the aquaculturist also must ensure that a specific water source has a suitable quantity of water for the production of a particular species. *Both water quality and quantity are of utmost importance to aquaculture.*

With respect to ensuring the safety of human consumers of aquatic foods, even if the culture species (or wild fishery stock) was able to grow and thrive in a given water source, low levels of pollutants or biological organisms can cause the products to be contaminated or have off-flavour.

As described by Zweig et al. (1999), the process by which pollutants concentrate in aquatic foods is called bioaccumulation. Entry of pollutants into an aquatic organism can be through the gills, the gut, or by direct exposure to the skin. Many pollutants, especially those which are fat soluble, collect in the tissues of aquatic organisms. This process results in higher concentrations of pollutants in body tissues of aquatic organisms than in the surrounding water. This can produce a potential health risk in human consumers of these organisms.

In Section 4.4.5, the relationship between contaminant concentration in source water and/or tissues of food species with the protection of human consumers is discussed. A model is described which shows the relationship of contaminants in culture feeds and/or source waters with human food residues. The model provides a means of predicting contaminant concentrations in the final aquaculture product given the concentrations in culture feeds and source waters.

Another problem is off-flavour or tainting which occurs when certain pollutants, such as petroleum hydrocarbons or metals, accumulate in aquatic organisms to a level at which the flavour is affected, making the product undesirable for human consumption (Zweig et al. 1999). This is discussed in Section 9.4.3.3.

9.4.1.3 Philosophy behind setting the water quality guidelines

The objective was to develop a set of water quality guidelines that would:

- promote the quality of water necessary for use by the aquaculture industry;
- protect human consumers of harvested aquatic food species.

1. Aquaculture guidelines

No comprehensive compilation of water quality guidelines for the protection of aquaculture species has been available in Australia. Most aquaculturists have relied on documents outlining general practices for specific species, often depending on their own experiences and use of qualitative information. According to Busby (pers comm), the situation is different in New Zealand where IAIS 005.1 (Industry Agreed Implementation Standards — which is law pursuant to the *Meat Act 1981*) has clear requirements on the mandatory water quality requirements for aquaculture. This standard has been successfully used in court hearings regarding abuse of water quality.

The water quality guidelines provided here will be of great benefit to the aquaculture industry in Australia and New Zealand. They have been developed to assist water resource managers to maintain an appropriate level of water quality where aquaculture activities exist, or may exist in the future. Farmers will now have a scientifically determined set of water quality targets which are designed to protect the quality of their culture waters. As well, the guidelines provide a quick reference guide for industry and researchers to ensure the quality of the source water.

They are not intended specifically to regulate activities of the aquaculture industry, although the aquaculturist must be concerned with the potential for downstream impacts on ambient water quality where effluent discharge occurs. The guidelines also should assist in providing a baseline for negotiations between farmers, governments and other relevant groups, and to protect waters used for aquaculture. The guidelines also should assist proponents of new aquaculture ventures to select areas with adequate water quality.

The water quality guidelines will provide the basis for aquaculture management decisions, such as:

- environmental planning and management
- environmental assessment and monitoring requirements
- appropriate environmental zoning and legislation
- appropriate species and suitable site selection
- site capacity
- farm design criteria
- stocking densities
- feeding activity
- production schedules.

It also is recognised that farms can impact on each other. For example, effluent from one farm may become the influent water for another. Thus, the numbers and sizes of farms which can be built in an area may need to be limited. Farms can also impact on other users of the waters, and operators need to comply with a number of government regulations as to the quality of their effluent water.

2. Human food safety guidelines

Standards for chemical contaminants in food for the protection of human consumers of aquatic foods have been set by the Australia New Zealand Food Authority (ANZFA) and are statutory.

ANZFA develops and administers uniform standards for contamination in foods under a treaty between Australia and New Zealand. These standards identify a limit to contamination in food (including aquatic foods) above which is considered injurious to human health, and are measured as concentrations in the flesh of organisms (mg/kg). The standards are listed in the *Food Standards Code* (ANZFA 1996) which is regularly updated for the protection of public health and safety. Unlike the water quality guidelines, food standards are enforceable through legislation.

The relationship between contaminant concentration in water and consequent concentration in the flesh of aquatic organisms is not well known and it has not been possible to provide water quality guidelines that will guarantee that the Australian and New Zealand food standards will be achieved. To provide some guidance to the users of this document the food standards for a number of contaminants are repeated in this Chapter, however, the reader is referred to the *Food Standards Code* which is the authoritative document on this issue. These standards are continually under review and can be examined on the appropriate web sites — www.anzfa.gov.au (Australia) or www.anzfa.govt.nz (New Zealand).

The guidelines provided here will assist in expanding demand for aquatic foods. For example, the reduction or minimisation of exposure to chemical residues, toxins and off-flavour compounds, will improve overall product quality. It is possible that clean waters will be used as a marketing tool, enhancing the ‘green’ image of aquaculture products and the sensory (taste) perceptions which can lead to premium market prices.

9.4.1.4 Approach to deriving water quality guidelines

Based on the approach undertaken in South Africa (DWAF 1996), a list of water quality indicators and contaminants was distributed to industry and researchers to determine the relative level of importance for aquaculture as well as for human food safety. Responses were provided with respect to the likelihood of exposure of adult stock under normal growing conditions in Australia and New Zealand, (i.e. under usual water quality conditions without exposure to major pollution). A wide variety of physico-chemical conditions as well as exposure to inorganic and organic toxicants and pathogenic organisms were considered important.

The guidelines are provided under four main categories:

- physico-chemical stressors
- inorganic toxicants (heavy metals and others)
- organic toxicants (pesticides, detergents, petrochemicals, etc.)
- pathogens and biological contaminants.

1. Scope of the study

The guidelines:

- Are concerned with the quality of water required to carry out aquacultural activities. The quality of effluent discharges are dealt with under a number of State and Federal Government regulations.
- Consider those contaminants, chemicals, elements, microorganisms, toxins, etc, likely to present a problem for aquaculture.
- Are concerned with protecting the health of culture species during the growing period (pre-harvest), but not during those processes (e.g. slaughter, processing, transport, marketing) considered to be post-harvest.
- Consider the effects on adult forms of cultured species, although it is recognised that hatcheries and nurseries also utilise large quantities of water (larval and juvenile stages of the life cycle usually have lower tolerance levels than the adult stages of the life cycle).¹
- Consider the protection of human consumers of harvested aquatic food species from the toxic effects of contaminants and from tainted flesh. This applies to aquaculture enterprises as well as recreational and commercial harvesting of aquatic food species from natural waters.

2. Methodology

Species groups

As there are more than 100 species currently cultured in Australia and New Zealand, a comprehensive literature review of the information available for all these species was not considered appropriate here. It was also recognised that the paucity of information with regard to Australian and New Zealand culture species would make compilation of data to set the guidelines difficult. Instead, all finfish, molluscan and crustacean species were divided into eight indicative groups so that efforts could be concentrated on reviewing the data for one or two common species.

Representative species for each group were chosen based on the level of production (i.e. commercial or experimental) and availability of scientific data.

The groups, representative species, their occurrence and their status are summarised in table 9.4.1 (equivalent to table 4.4.1 in Chapter 4, Volume 1). The classification suggested by Lawson (1995) is used to determine the salinity requirements of the species groups, e.g. saltwater or marine species are those which prefer salinities between 33 and 37 g/L (ppt), for estuarine or brackish water species it is 3 to 35 ppt, while freshwater species prefer below 3 ppt.

As indicated in table 9.4.1, a range of aquatic plants, reptiles and invertebrates which are cultured are not included in the list of representative species. At present the production of these species which were left out contributed less than 1.5% of the total value of aquaculture production in Australia in 1997/98 (O'Sullivan & Roberts 1999). Whilst no figures are available for recreational and indigenous fishery, their contribution is thought to be close to zero. Likewise with the commercial fisheries, an examination of the Australian Fisheries Statistics for 1998 (ABARE 1999) shows no specific production data for these species. In New Zealand it is

¹ Given that larval and juvenile stages are invariably the most sensitive to water quality, additional research is required to redress this deficiency. Until this is done, operators of hatcheries and nurseries should use special water treatment to ensure that the water to which the larvae/fry are exposed is the best possible quality.

presumed that the situation would be much the same. Thus the authors feel justified in confining the data collation to the species groups provided in table 9.4.1.

Table 9.4.1 Representative species, occurrence and culture status

Species group	Representative species ^a	Occurrence	Aquaculture Status ^b
freshwater fish	rainbow trout	Australia/New Zealand	commercial/none
	silver perch	Australia	commercial
marine fish	snapper	Australia/New Zealand	commercial/commercial
	flounder/whiting	Australia/Australia	experimental/experimental
brackish water or euryhaline fish	barramundi	Australia	commercial
	black bream	Australia	experimental
freshwater crustaceans	marron	Australia	commercial
	yabbies	Australia	commercial
	red claw	Australia	commercial
	freshwater shrimp	Australia/New Zealand	experimental/commercial
marine crustaceans	black tiger prawns	Australia	commercial
	kuruma prawns	Australia	commercial
edible bivalves	Sydney rock	Australia	commercial
	Pacific oysters	Australia/New Zealand	commercial/commercial
	blue mussels	Australia/New Zealand	commercial/none
	green shell mussels	New Zealand	commercial
pearl oysters	golden lip	Australia	commercial
gastropod/molluscs	abalone/paua	Australia/New Zealand	commercial/commercial
	trochus	Australia	experimental

a The groups of aquaculture species not included in this list are: seaweeds and aquatic plants; crocodiles; a range of live feed and microalgal species; sea cucumbers (beche-de-mer), sponges and other invertebrates.

b Commercial = products offered for sale; Experimental = production but no sales; None = species occurs but there is no culture undertaken.

Data sources

The information used to derive these water quality guidelines was collated during a comprehensive review of the appropriate levels in relevant literature, databases, documents and the internet, including:

- previous Australian and New Zealand Environment Conservation Council (ANZECC) guidelines;
- Australian and New Zealand National Food Authority and state health departments standards and guidelines;
- Australian/New Zealand and international shellfish sanitation programs' requirements;
- Australian Quarantine Inspection Service requirements for seafood export;
- World Bank, South African (freshwater only), European, Canadian and USA aquaculture and general water quality guidelines;
- aquaculture textbooks and reviews;
- extensive industry and expert review of criteria and guidelines including mail surveys, guideline reviews and telephone discussions;
- database searches, specifically CD ROM: ASFA 1978–1987; ASFA 1988–6/96; *Life Sciences* 1982–1985, 1986–1989, 1990–1992, 1993–1995, 1/96–6/96; *Current Contents* 1993–1996.

The following key words were used to search these databases: rainbow trout, *Oncorhynchus mykiss*, barramundi, *Lates calcarifer*, sea perch, silver perch, *Bidyanus bidyanus*, snapper, sea bream, flounder, prawn, *Penaeus monodon*, crustaceans, mussels, *Mytilus edulis*, oyster, *Crassostrea gigas*, pearl oyster, abalone, *Haliotis*, gastropod, Atlantic salmon, *Salmo salar*, *Salmo gairdneri*, yabbie, marron, redclaw, *Cherax destructor*, crayfish, NOEC, LC₅₀, EC₅₀, tolerance, water quality guidelines, toxicants, pesticides and biocides, toxicity, hazardous chemicals, effects, sublethal responses, turbidity, suspended solids, secchi, heavy metals, Australia, salinity, brackish water, freshwater, marine, pollution, pollutants, environmental pollutants, dissolved oxygen, temperature, ammonia, pH, acidity, alkalinity, survival.

This dataset review was relatively comprehensive, however, due to resource limitations, some of the sources which are more difficult to access were not included in the search strategy. Some unpublished data, research theses, governmental reports, internal reports, and scientific papers published in journals not listed in databases or published in languages other than English, were not accessible. Also some of the information included in the review is based on data from database abstracts only.

Due to the paucity of information for many water quality parameters, recommended ranges for culture were also used. Often, these data were obtained from 'personal communications' with practitioners in this field which were either based on experimental, but non-published, evidence, or on experience. Clearly, any information that has not undergone peer review must be considered with less confidence than information which has been subject to some level of external scrutiny. Further discussion on level of confidence that should be put in the guidelines for aquaculture and harvesting of aquatic foods is provided in Section 9.4.1.5.

Where possible, relevant data on tolerances and toxicity for one or two representative species were collated. These data were summarised for each species group and used to formulate the interim water quality guidelines in Section 9.4.2. A précis of relevant scientific and technical information, together with references, is provided as the rationale for each guideline. Where discrepancies in the data were identified, the more conservative data were generally used. If data for specific water quality parameters could not be found, appropriate data for other species were used to build a data resource for each group. The source information for the aquaculture guidelines was compiled into an aquaculture database which can be accessed on the Guidelines CD-Rom.

For the protection of human consumers of aquatic foods a search of the available data found insufficient information for deriving water quality guidelines that would ensure the Australian and New Zealand food standards would be met. Relevant food standards from the *Food Standards Code* (ANZFA 1996, and updates) established by the Australia New Zealand Food Authority have therefore been provided as guidance. Discussion is provided in Section 9.4.3.

9.4.1.5 Discussion on confidence levels

1. Protection of cultured fish, molluscs and crustaceans

To determine guidelines for each of these water quality parameters, a search of the data-set (Section 9.4.1.4/2) was undertaken for a number of measurements, including:

- no observed effect concentration (NOEC);
- lowest observed effect concentration (LOEC);
- effective concentration (EC₅₀) plus a description of effect;

- concentration to kill 50% of test population (LC₅₀) (the 96 hr exposure period was preferred).

NOEC and LOEC measurements were the most suitable to determine 'safe' levels for protection of aquaculture species. However, the 96 hr LC₅₀ was also used, based on the recommendation by Boyd (1990) that an application factor of 0.1 or 0.05 times the lowest 96 hr LC₅₀ value may be used to estimate a 'safe' concentration of a potential toxicant for aquaculture species. For example, if the 96 hr LC₅₀ of a substance is 0.1 mg/L, a concentration of 0.01 mg/L or 0.005 mg/L may be considered safe for prolonged exposure. Although Boyd (1990) noted that this practice involved some uncertainties, this method has been used in the United States and Japan to establish water quality guidelines for the protection of aquatic animals and plants. However, there can be potential sub-lethal effects on growth or resistance to pathological organisms (R Cordover, pers. comm. 2000).

MATCs — maximum acceptable toxicant concentrations — are often used to indicate *safe* levels. A MATC is equal to the lowest concentration which have been reported to harm organisms in laboratory toxicity (e.g. 96 hr LC₅₀) tests multiplied by an application factor. The *safe* levels recommended by many overseas government agencies (e.g. USEPA, EIFAC, CCME, DWAF) are conservative estimates as they use application factors ranging from 1/10 to 1/100 (Boyd 1989).

In most cases there is a good data set for establishing physico-chemical water quality guidelines for the protection of aquacultural production (Section 9.4.2.1). However, the paucity of information on the effect of inorganic and organic toxicants and biological contaminants on aquaculture species has severely limited the number of water quality guidelines that could be established (Sections 9.4.2.2, 9.4.2.3 and 9.4.2.4, respectively). Where specific water quality guidelines are not available for the protection of aquaculture species, guidelines for the protection of aquatic life (Chapter 3, Volume 1) could be utilised but these are likely to provide a more conservative guideline value.

For those water quality guidelines protecting aquaculture production a high level of credence can be assumed where referenced sources have been used, particularly with review papers such as Boyd (1989, 1990), Meade (1989), Pillay (1990), Svobodova et al. (1993), Schlotfeldt and Alderman (1995), DWAF (1996) and Zweig et al. (1999).

Every care has been taken with the use of personal communications, which are sometimes based on scientific data (although un-referenced) and, at other times, anecdotal evidence. Although the advice is of high quality, attempts to find the required data through scientific experimentation should be made where possible.

The water quality guidelines listed in this Chapter can be used with reasonable confidence to assess ambient water quality for aquacultural uses. If ambient water quality exceeds the guidelines for any parameter then there is a high risk of an impact on aquacultural activities, and further work should be undertaken to better define the risks and potential impacts. However, even though there is a low risk if ambient water quality remains below the guidelines, this cannot be taken as a guarantee that problems will not occur in the future.

2. Protection of human consumers of aquatic foods

The ANZFA food standards for contamination of aquatic foods are legally binding and must be adhered to.

9.4.2 Water quality guidelines for the protection of cultured fish, molluscs and crustaceans

These water quality guidelines are provided as a general guide for aquaculture in Australia and New Zealand. Where specific water quality guidelines for the protection of aquaculture species cannot be made, guidelines for the protection of aquatic ecosystems (Chapter 3) can be used.

Given the large number of different aquaculture production systems and species utilised in Australia and New Zealand, across a wide range of environmental conditions, it should not be assumed that one set of specific values will apply equally in all situations. Local, site-specific information will be needed to supplement the broad information provided in this Chapter.

A decision tree for the determination of water quality guidelines for the protection of aquaculture species is provided in figure 4.4.1 in Volume 1. Specialist assistance may be required to complete those steps where chemical speciation/complexation must be taken into account (Section 3.4.3), and likewise to conduct toxicity tests should they become necessary. A user can make a decision on the risk-based framework and leave the process at any level, however, the further through the process one moves, the greater the confidence in the level of risk.

Tables 9.4.3–9.4.43 provide the water quality guidelines for general freshwater and saltwater (brackish and marine water) aquaculture uses. Where information is available on the specific water quality requirements for each of the species groups in table 9.4.1, it has been included in Section 9.4.2 and should be referenced where guidance is sought for particular species groups. Section 9.4.2 also contains a short discussion for many water quality parameters describing how the guidelines were formulated.

It is worthwhile considering a worked example to demonstrate how the decision tree can be used. An aquaculture company wishes to grow prawns (such as *Penaeus monodon*). They begin by testing the basic (physico-chemical) water quality parameters to obtain a characterisation of the site they wish to use for the prawn culture. Based on recommendations of a prawn farming consultant they test for alkalinity, dissolved oxygen, hardness, pH, salinity and suspended solids. These are provided in table 9.4.2 and when compared with the general saltwater and prawn specific guidelines the site characterisation appears adequate.

However, the company also has several decisions to make regarding the other parameters being outside the guidelines range:

- With respect to dissolved oxygen the site's water quality is below the recommended limit (table 9.4.7) and the farmer would have to undertake additional management to ensure the prawns will grow (e.g. use aerators). This becomes an economic decision, although tests may be required to determine why the source water is low in dissolved oxygen (may be a sign of organic pollution).
- Salinity at times is at the bottom end of the recommended range (table 9.4.11) and an assessment would need to be made if this would adversely affect production.
- Hardness is quite low compared to the guidelines (table 9.4.9), and again the decision on whether to take steps to alter this (i.e. the addition of limestone) has to be made.

Table 9.4.2 Site characterisation at proposed prawn farm site compared to general and species specific guidelines

	General Saltwater Guidelines (usually mg/L)	Prawn Specific Guidelines (usually mg/L)	Site characterisation (usually mg/L)
Physio-chemical stressors			
Alkalinity	>80	>80	86–89
Dissolved oxygen	>5	>5	>3
Hardness	>50	150–400	40
pH (pH units)	6.6–8.0	6–9	8.2
Salinity	0–36	>15–30	12–22
Suspended solids (Organic matter)	<75	<75	70
Inorganic toxicants			
Cadmium	<0.0005	<0.053–0.15	0.0003
Hydrogen sulphide	<0.002	<0.002	0.001
Organic toxicants			
Endosulfan	0.001	0.01	not detected in water or sediments
Malathion	None provided f/w <0.1	0.001	0.002 (water) 0.003 (sediments)

Overall, through discussions with the other prawn farmers in the region, the company decides that the additional work required to keep the oxygen, salinity and hardness levels within that required for prawns, can be maintained economically year round. The company determine that from the point of view of the physio-chemical parameters there is low risk (i.e. the water quality is acceptable) in utilising that particular site for prawn farming.

It becomes a lot more complicated with the various toxicants as site or regional specific environmental factors (such as water hardness, dissolved organic matter and turbidity) can significantly influence the availability and/or the effects of a contaminant to the culture organism. Given the large number of chemicals and biological contaminants (Sections 9.4.2.2, 9.4.2.3 and 9.4.2.4), and the high cost of measurement of many contaminants (particularly the pesticides and other organic toxicants), some assistance is required in selecting which ones to test for. The basis for measurement of inorganic chemicals, organic toxicants and organisms might be experience from other farms in the area, or a history of potential pollutants in the water source.

Again through discussions with other prawns farmers, consultants and local government authorities, the aquaculture company determines that there are a number of potential contaminants. A consideration of the factors affecting toxicity (hardness, metal bioavailability, bioaccumulation; refer to Section 8.3, Volume 2) shows that the main inorganic chemicals of concern are cadmium and hydrogen sulphide, whilst the pesticides Endosulfan and Malathion have been used in the area for banana farming so they could also be of concern.

Water and soil (sediment) samples were taken and analysed in a registered laboratory and the inorganic chemicals were found to be within the guidelines range, although the company was warned that cadmium can be of concern from a human food safety viewpoint (Section 4.4.5). No Endosulfan was detected, however, the levels of Malathion in both the water and the sediments were higher than that recommended for black tiger prawns (table 9.4.41), however, no guidelines were available for saltwater.

A series of acute and chronic toxicity tests undertaken by the local university showed that the prawns were not adversely affected and there were no human food safety concerns.

Therefore the company found that the sources waters were of low risk for their planned prawn farm.

9.4.2.1 Physico-chemical parameters

A number of basic parameters need to be tested in all water sources used for aquaculture, including dissolved oxygen, hardness, salinity and temperature. Many of these parameters are also regularly monitored in the culture system to ensure that the aquatic organisms are being held in conditions conducive to survival and growth.

1. Alkalinity

Alkalinity relates to the capacity of the water to accept protons and is a measure of the water's buffering (acid neutralising) capacity when considered in conjunction with other water quality parameters (i.e. CO_2). The alkalinity of water is the amount of carbonates, bicarbonates, hydroxides and, to a lesser extent, silicates, borates, phosphates and organics (Klontz 1993). It is expressed as mg CaCO_3/L or as mEq/L — the number of milliequivalents of hydrogen ions which are released by 1 kg of water when an excess of acid is added (Strickland & Parsons 1968).

The chemical composition of rocks and soils strongly influences the natural alkalinity of water, which can range from very low values to several hundred mg/L CaCO_3 (DWAF 1996, Zweig et al. 1999). Waters with moderate to high alkalinity tend to be more strongly buffered than waters with low alkalinity. Seawater has a mean total alkalinity of 116 mg/L (Lawson 1995).

Guideline notes

Zweig et al. (1999) state there are no direct effects of alkalinity on fish and shellfish, however, it is an important parameter due to its indirect effects, including the protection of aquatic organisms from major changes in pH. In addition, in low alkalinity waters, where CO_2 and dissolved carbonates are at low concentrations, photosynthesis may be inhibited, thus restricting phytoplankton growth (Lawson 1995). DWAF (1996) considers that alkalinity below 20 mg CaCO_3/L is less suitable for fish culture due to the associated unstable water chemistry, while levels above 175 mg CaCO_3/L reduces natural food production in ponds which, in turn, leads to below optimal production. Tucker and Robinson (1990) suggest that a range between 20 and 400 mg/L is sufficient for most aquaculture purposes, although the desirable level is ≥ 100 or 150 mg/L. Tyco (pers comm 1999) stated that many surface waters in Australia have alkalinities from 10 to 30 mg/L and support fish. Thus, a guideline level of ≥ 20 mg/L is recommended for freshwater species (table 9.4.3).

Salt water is slightly alkaline and has a strong buffering capacity (Kulle 1971) so alkalinity is not usually of concern for most seawater and brackish water aquaculturists. However, Meade (1989) suggested a range of 10 to 400 mg/L for saltwater species, so a guidelines level of >10 mg/L is recommended for all saltwater culture species (table 9.4.3).

See also discussion under pH (Section 9.4.2.1, no.8).

Table 9.4.3 Summary of the recommended water quality guidelines for alkalinity

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	≥20 >10	freshwater saltwater	DWAF (1996) based on Meade (1989)
General	≥20 >10–400 ≥100–150	freshwater saltwater most aquaculture purposes	DWAF (1996) Meade (1989) Tucker & Robinson (1990)
Freshwater fish	20–400 20–200 20–175 20–400 15–20	silver perch rainbow trout freshwater species silver perch salmonids	Rowland pers comm Forteath pers comm DWAF (1996) Rowland (1995a) SECL (1983)
Marine fish	>20 >100	Atlantic salmon (in sw)	Swindlehurst pers comm Klontz (1993)
Brackish water fish	>5	barramundi	Curtis pers comm
Freshwater crustaceans	50–100 50–300 50–150	redclaw yabbies marron	Jones (1990) Wingfield pers comm Wingfield pers comm
Marine crustaceans	>80		Swindlehurst pers comm
Edible bivalves	>20		Swindlehurst pers comm
Non edible bivalves	>20		Swindlehurst pers comm
Gastropods	>20		Swindlehurst pers comm

2. Biochemical oxygen demand (and COD)

The biochemical oxygen demand (BOD) is a measure of the combined biological and chemical demand on dissolved oxygen in a system. It is a measure of the amount of oxygen required by bacteria, algae, sediments and chemicals over a set period of time. BOD is of importance in aquaculture because microbial degradation of organic matter is a major sink for dissolved oxygen, a highly important parameter for aquaculture (Zweig et al. 1999).

Aquaculture operations should not utilise waters which are polluted with chemicals and/or excessive nutrients. Thus, BOD becomes an important parameter for aquaculture. Increasing levels of BOD indicate organic pollution which is a cause of concern for aquaculturists (Schlotfeldt & Alderman 1995).

BOD is often measured as the five day BOD (BOD₅), defined as the amount of dissolved oxygen consumed by microorganisms in the biochemical oxidation of organic matter over a 5 day period at 20°C. However, for aquaculture operations, the time period and temperature conditions under which BOD is estimated can be modified, with the resultant value being expressed as a function of time (i.e. mg L⁻¹ hr⁻¹) (Zweig et al. 1999).

Some regulatory authorities, e.g. Queensland's Environmental Protection Agency, are moving away from monitoring requirements for this parameter because of the difficulty of measuring and the availability of better indicators for aquaculture. According to Semple (pers comm) total organic carbon (TOC) is a more direct and effective measure of the environmental impact of an effluent stream than BOD₅ and it allows timely intervention in the operations. Recent research undertaken by Brisbane Caltex Refineries has demonstrated that BOD₅ can be effectively correlated to TOC with a 95% confidence level.

Chemical oxygen demand (COD) is a theoretical maximum measure of the amount of oxygen required by the chemicals in a water source. It is usually only significant where high concentrations of chemicals are in the water, e.g. effluent from factories.

Guideline notes

As most aquaculture activities can increase BOD, a low background level is preferred. Svobodova et al. (1993) noted that the BOD₅ for cyprinids is 8 to 15 mg/L while for salmonids the corresponding levels are up to 5 mg/L (both depend on the intensity of the culture system and the rates of aeration).

For freshwater species, the COD and BOD guidelines suggested by Schlotfeldt and Alderman (1995) are used as the recommended guideline (table 9.4.4). Little information is available for marine species, so no guideline is provided.

Svobodova et al. (1993) noted that the COD maximum level for cyprinid culture is 20–30 mg/L while for salmonids the corresponding levels are up to 10 mg/L (both depend on the intensity of the culture system and the rates of aeration). The COD level for saltwater is yet to be determined.

The guidelines can be used while taking into account factors such as dissolved oxygen requirements of the culture species, the degree of pond aeration, seasonal temperature fluctuations, expected photosynthetic activity, and oxygen solubility. A resultant judgement can be based on the appropriate BOD for the source water (Zweig et al. 1999).

See also discussions under Dissolved oxygen (9.4.2.1/5) and Suspended solids (9.4.2.1/10).

Table 9.4.4 Summary of the recommended water quality guidelines for biochemical oxygen demand

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	<15	freshwater BOD ₅	Schlotfeldt & Alderman (1995)
	<40	freshwater COD ₅	Schlotfeldt & Alderman (1995)
	ND	saltwater BOD ₅	
	ND	saltwater COD ₅	
General	<15	freshwater BOD ₅	Schlotfeldt & Alderman (1995)
	<40	freshwater COD ₅	Schlotfeldt & Alderman (1995)
Freshwater fish	<10	rainbow trout BOD	Forteach pers comm
	<12	freshwater species BOD	DWAF (1996)
	<30	rainbow trout COD	Forteach pers comm
	<5	salmonids BOD	Svobodova et al. (1993)
	<10	salmonids COD	Svobodova et al. (1993)
Marine fish	<10	BOD ₅	Swindlehurst pers comm
Brackish water fish	<20	BOD ₅	Swindlehurst pers comm
Freshwater crustaceans	<10	BOD ₅	Swindlehurst pers comm
Marine crustaceans	<10	BOD ₅	Swindlehurst pers comm
Edible bivalves	<10	BOD ₅	Swindlehurst pers comm
Non edible bivalves	<20	BOD ₅	Swindlehurst pers comm
Gastropods	<10	BOD ₅	Swindlehurst pers comm

ND Not determined — insufficient information

3. Carbon dioxide

Carbon dioxide is a natural component of surface water. It is dissolved in water in its molecular gaseous states; only 10% is in the form of carbonic acid, H₂CO₃. These two forms of carbon dioxide together constitute what is termed free CO₂. The ionic forms (i.e. fixed carbon dioxide) are represented by the bicarbonate and carbonate ions (HCO₃⁻ and CO₃²⁻ respectively). Their presence is important for the buffering capacity of the water (Svobodova et al. 1993).

The level of carbon dioxide in the water is related to photosynthetic activity of aquatic plants and respiration of these plants and aquatic animals, as well as bio-oxidation of organic compounds. Dissolved carbon dioxide forms carbonic acid, causing a drop in pH. Likewise, its removal during (algal) plant photosynthesis causes the pH to climb (Walker 1994). At equilibrium, freshwater contains about 2.0 mg/L CO₂ (Klontz 1993) and seldom rises above 20 to 30 mg/L (Svobodova et al. 1993). In waters used for intensive fish culture, free carbon dioxide levels typically fluctuate from 0.0 mg/L in the afternoon to 5 to 10 mg/L at daybreak (Boyd 1990). Zweig et al. (1999) warned that extraordinarily high (toxic) levels of CO₂ can be found in ground waters.

High concentrations of carbon dioxide have a narcotic effect on fish and even higher concentrations may cause death; however, such concentrations seldom occur in nature.

The direct adverse effects can occur when there is an excess of free CO₂, especially in waters low in dissolved oxygen. This latter situation can occur when too much free CO₂ is utilised for photosynthesis of phytoplankton, or when water is vigorously aerated with CO₂ free air. Free CO₂ concentrations below 1 mg/L affect the acid-base balance in fish blood and tissues and cause alkalosis (Svobodova et al. 1993). Fish suffering from free CO₂ deficiency gather close to the water surface and show symptoms of suffocation even though the concentration of oxygen in the water is adequate (Taege 1982).

The toxic action of carbon dioxide is either direct or indirect. The indirect action of both free and bound CO₂ is exerted on fish through its influence on water pH, especially where the values rise to toxic levels (Svobodova et al. 1993). Also, changes in pH affect the toxicity of those chemicals which exist in the dissociated and nondissociated forms of which only one is toxic, such as H₂S and ammonia.

Most aquaculture species will survive in waters containing up to 60 mg/L carbon dioxide provided that dissolved oxygen concentrations are high (Boyd 1989); however, SECL (1983) suggested the carbon dioxide levels should be kept below 20 mg/L for salmonid hatcheries. Unfortunately, carbon dioxide concentrations normally are high when dissolved oxygen concentrations are low.

Guideline notes

Meade (1989) suggested a range of 0 to 10 mg/L for aquaculture. Pillay (1990) recommended that levels should not be above 3 mg/L for most farmed finfish. For freshwater species DWAF (1996) recommended below 12 mg/L and Schlotfeldt and Alderman (1995) below 25 mg/L so a median level of <10 mg/L is recommended as the guideline for freshwater aquaculture (table 9.4.5). For saltwater species the guideline is recommended at <15 mg/L which is the lowest of those provided for the groups in table 9.4.5.

4. Colour and appearance of water

These are not highly objective measurements but many fish farmers and crustacean farmers attach a lot of significance to these two properties of pond water. Colour is a result of the interaction of incident light and impurities in the water (Lawson 1995). There are three common causes of water colouration and variations in water appearance:

- suspension of silt and clay particles
- significant growth of plankton, particularly microalgae
- suspension of humic acids and other organic acids

Table 9.4.5 Summary of the recommended water quality guidelines for carbon dioxide

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	<10	freshwater	Professional judgement
	<15	saltwater	Professional judgement
General	<10	aquaculture	Meade (1989)
	<12	freshwater	DWAF (1996)
	<25	freshwater	Schlotfeldt and Alderman (1995)
Freshwater fish	<10	rainbow trout	Pillay (1990), Forteath pers comm
	<6	rainbow trout	Holliman (1993)
	0–15	silver perch	Rowland (1995a)
	<3	farmed fish	Pillay (1990)
Marine fish	<15		Swindlehurst pers comm
Brackish water fish	<15	barramundi	Curtis pers comm
Freshwater crustaceans	<15		Wingfield pers comm
Marine crustaceans	<25		Swindlehurst pers comm
	<20	prawns	Boyd & Fast (1992)
Edible bivalves	<25		Swindlehurst pers comm
Non edible bivalves	<25		Swindlehurst pers comm
Gastropods	<25		Swindlehurst pers comm

Generally, when farmers refer to the ‘colour’ of the water, they are actually referring to turbidity due to significant silt and clay particle accumulation, or growth of phytoplankton and zooplankton.

Colouration of surface water in rivers and creeks (e.g. humic acids and organic acids), although not due to suspended particles, acts in a similar way with regard to light penetration. This type of water colouration may be beneficial in tank and cage culture as it shades fish and prevents sunburn as well as reducing plant biofouling. However, it may cause difficulties for growers in observing their stock.

Lawson (1995) reported that impending oxygen shortages in the water can often be detected by changes in colour.

Although high colour may shade fish and impede algal growth, it is usually due to tannins. These are phenols which bind with protein and at high levels may affect fish respiration, particularly with sensitive fish species (such as rainbow trout).

Guideline notes

ANZECC 1992 recommended a less than 10% change in euphotic zone for freshwater and saltwater ecosystem protection. Measurement of colour is difficult and is not usually undertaken by farmers. O’Connor (pers comm) suggested 30–40 platinum-cobalt (Pt-Co) units (refer to APHA/AWWA/WEF 1995 for a description of this method) as a good starting point for a recommended guideline (table 9.4.6).

See also discussion under Suspended solids and turbidity (9.4.2.1/10).

Table 9.4.6 Summary of the recommended water quality guidelines for colour

Group	Guideline Pt-Co units	Comments	Reference
Recommended guideline	30–40	freshwater and saltwater	O’Conner pers comm

5. Dissolved oxygen

Dissolved oxygen (DO) is a very basic requirement for aquaculture species (Zweig et al. 1999). However, the amount of oxygen available to aquatic animals is approximately only 0.0015% (w/v maximum) compared with 21% available in air. Boyd (1989) considered that dissolved oxygen is the most critical water quality variable in aquaculture. Anoxia occurs when dissolved oxygen levels in the environment decrease to the point where aquatic life can no longer be supported. In suboptimal dissolved oxygen levels, growth is slowed. Dissolved oxygen is usually expressed in mg/L, ppm or partial pressure.

Some species are more resistant to low levels of oxygen than others. Boyd (1990) noted that the amount of oxygen required by aquatic animals is quite variable and depends on species, size, activity (levels increase with activity), water temperature (doubles with every increase of 10°C), condition (lean fish consume less than fat fish), DO concentration, etc. Other species are air breathers and are able to be farmed under intensive conditions with very low levels of dissolved oxygen and poor water quality (e.g. catfish, eels, aquatic reptiles).

Some species have a greater affinity for oxygen (higher levels of haemoglobin and similar complexes in blood) and, therefore, are more tolerant of low levels. This also relates to the partial pressure of dissolved oxygen in the water and its ability to exchange across gill membranes. This, in turn, governs the minimum oxygen concentration to survive, grow, etc, and is approximately the minimum recommended concentration (Purser 1996 a,b).

Daily fluctuations in impounded waters are higher than those in the open sea or running waters. The DO concentration can fluctuate in response to photosynthesis of aquatic plants and respiration of aquatic organisms. Daily fluctuations are such that the lowest DO concentrations occur soon after sunrise with levels higher in the late afternoon (Boyd 1990).

In ponds, tanks and other enclosed culture systems, mechanical aeration can be used to lift dissolved oxygen levels, while water movement from currents and tides assists in open culture systems. Pure oxygen (oxygenation) may be used to supplement dissolved oxygen levels, particularly in intensive culture systems.

The factor most frequently responsible for a significant reduction in the oxygen concentration of the water (oxygen deficiency) is pollution by biodegradable organic substances (including waste waters from agriculture, the food industry and public sewage). These substances are decomposed by bacteria which use oxygen for this process (Svobodova et al. 1993). The most common cause of low DO in an aquaculture operation is a high concentration of biodegradable organic matter in the water, resulting in a high BOD. This problem is further exacerbated at high temperatures (Zweig et al. 1999).

Guideline notes

As suggested by Zweig et al. (1999), setting DO guidelines for source water is difficult as DO can be affected by many processes independent of the initial source water DO. Thus, at the site selection stage, the initial DO and BOD can be used to assess the ability of the source water to maintain appropriate oxygen levels. Other factors affecting DO concentration in aquaculture operations can only be assessed and if necessary mitigated once the operation is running (Zweig et al. 1999).

Meade (1989) said that dissolved oxygen levels above 5 mg/L provide protection for most aquaculture species and this level is recommended as the guideline (table 9.4.7).

See also discussions under Biochemical oxygen demand (9.4.2.1/2) and Temperature (9.4.2.1/11).

Table 9.4.7 Summary of the recommended water quality guidelines for dissolved oxygen

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	>5	freshwater and saltwater	Meade (1989)
General	>5	freshwater and saltwater	Meade (1989)
Freshwater fish	>6	coldwater species, & warmwater species	DWAF (1996), Lawson (1995)
	>5	rainbow trout	DWAF (1996)
	>6	rainbow trout	Pillay (1990)
	>4.5 (afternoon)	silver perch, optimal	Rowland (1995a)
	>3.0 (dawn)	silver perch, optimal	Rowland (1995a)
Marine fish	>7		Alabaster & Lloyd (1982)
	>6		Huguenin & Colt (1989)
Freshwater crustaceans	>5	can tolerate lower levels	Wingfield pers comm
	>3		Swindlehurst pers comm
Marine crustaceans	>5	prawns	Boyd (1989), Lee & Wickins (1992)
Gastropods	>3	abalone	Fallu (1991)

6. Gas supersaturation (total gas pressure)

Supersaturation of dissolved gas occurs when the pressure of the dissolved gas (total gas pressure; TGP) exceeds the atmospheric pressure. TGP refers to the sum of the partial pressures of dissolved gases in the water (i.e. oxygen, nitrogen and carbon dioxide).

Supersaturation can occur via a range of processes including an increase in temperature, mixing waters of different temperatures, air entrainment (e.g. as in a waterfall), photosynthesis, and bacterial activity (Lawson 1995). Supersaturation (especially in well or spring water used in hatcheries) can also occur when physical processes such as pressurised air injections are improperly applied, when rapid temperature increases occur, or when air bubbles are carried to great depths (Tomasso 1993). It also can occur where heaters are used, especially if the water is in pipes and under pressure.

Gas supersaturation can be caused by entrainment of air bubbles when water falls over high dams and often results in air leaks in pipes (Nebeker & Brett 1976), or improper submergence of the intake of pumps (Kils 1977), highly efficient submerged aerators (Colt & Westers 1982) and high levels of photosynthesis in ponds (Takashi & Yoshihiro 1975). It may also occur during fish transport, especially in aeroplanes where the pressure falls at altitude, or in road tankers where oxygen is used and in systems with oxygenation. In Tasmania, freshwater fish kills have been reported due to supersaturation of waters flowing out of a hydro-electric plant.

Nitrogen supersaturation is the main problem as it is the major (78%) component of air. The maximum level is around 103% of atmospheric pressure before problems occur. Water supersaturated with nitrogen is unable to carry adequate oxygen for fish (Klontz 1993).

Oxygen saturation up to 200–300% can be tolerated if oxygen is used directly or during photosynthesis (when air is used, nitrogen becomes the main component and problems can occur). It can cause massive distension of the swim bladder of salmonids, although the mortality is usually low (Klontz 1993). This can occur if the water supply is from highly vegetated streams on bright sunny days.

Gas-bubble disease is a problem related to the supersaturation of gases in water. Changes in pressure may cause bubbles to form in the blood and tissues of aquatic animals. This

phenomenon is known as gas bubble trauma which may cause acute or chronic problems, especially in eggs, larvae and juveniles.

The signs of this problem are pop-eye (exophthalmia, which is not always evident in cases of gas bubble disease, can also be due to other causes) and the presence of bubbles under the skin (easily visible in the fins and on the head) and in the gills. Fish suffering from this condition usually leap vigorously from the water before they die (Nowak 1996).

High carbon dioxide levels in fish transport systems (where ventilation is absent) can inhibit oxygen uptake.

Guideline notes

Although Svobodova et al. (1993) recommended that the N₂ levels at existing atmospheric pressure should be below 300%, DWAf (1996), Meade (1989) and SECL (1983) claimed dissolved oxygen levels should be much lower at between 103 to 105%. Lawson's (1995) conservative suggestion of a level of <100% (N₂ existing atmospheric pressure) is recommended as the guideline for both freshwater and saltwater aquaculture (table 9.4.8).

See also discussions under Dissolved oxygen (9.4.2.1 No.5).

Table 9.4.8 Summary of the recommended water quality guidelines for gas supersaturation

Group	Guideline	Comments	Reference
Recommended guidelines	<100%	freshwater & saltwater	Lawson 1995
General	<100% <103–105	freshwater	Lawson 1995 SECL (1983), Meade (1989) DWAf (1996)
Freshwater fish	<105%		Swindlehurst pers comm
Marine fish	<105%		Swindlehurst pers comm
Brackish water fish	<105%		Swindlehurst pers comm
Freshwater crustaceans	<120%		Swindlehurst pers comm
Marine crustaceans	<120%		Swindlehurst pers comm

7. Hardness

Total hardness primarily measures the concentration of all metal cations (usually dominated by calcium and magnesium in freshwater) in the water, with the exception of alkali metals (Zweig et al. 1999). Hardness is normally expressed as the level of calcium carbonate (CaCO₃) in mg/L and can be divided (Sawyer & McCarty 1978) into four categories:

- soft water has the range 0 to 75 mg/L;
- moderately hard water ranges from 75 to 150 mg/L;
- hard water ranges from 150 to 300 mg/L;
- very hard water is >300 mg/L CaCO₃.

Soft water is usually acidic while hard water is generally alkaline. Most fresh surface waters in Australia and New Zealand have a hardness between 10 and 400 mg/L as CaCO₃.

In soft waters, carbonate and bicarbonate salts are in short supply, so large pH swings can be common place. Hard water has been found to reduce the toxicity of several heavy metals (e.g. cadmium, chromium(III), copper, lead, nickel and zinc; SECL 1983), as well as ammonia and the hydrogen ion (Zweig et al. 1999).

Some aquacultural species have a specific requirement for calcium, for bone formation in fish and exoskeleton formation in crustaceans. Calcium is also necessary for proper osmoregulation, and the calcium ion generally reduces the toxicity of hydrogen ions, ammonia and metal ions. High calcium levels in freshwater can inhibit phytoplankton growth; however, blue-green algae are known to thrive in harder water (high Ca^{2+}) which can influence productivity of the pond water.

Guideline notes

Hardness averages 600 mg/L in ocean water and therefore is not a problem in seawater or brackish water systems (Lawson 1995). Desirable hardness levels vary for different freshwater species and groups of species as summarised in table 9.4.9.

Although species requirements vary markedly (table 9.4.9), Meade (1989) recommended a range between 10 and 400 mg/L for aquaculture. The recommended guideline range for freshwater species is 20–100 mg/L as proposed by DWAf (1996). In saltwater, the hardness requirement is not of concern (Lawson 1995).

Table 9.4.9 Summary of the recommended water quality guidelines for total water hardness

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	20–100	freshwater	DWAf (1996)
	NC	saltwater	Lawson (1995)
General	20–100	freshwater	DWAf (1996)
	NC	saltwater	Lawson (1995)
	10–400	aquaculture	Meade (1990)
Freshwater fish	20–300		Boyd & Walley (1975), Romaine (1985)
	50–100	rainbow trout	Forteach pers comm
	10–160	silver perch	Rowland pers comm
	10–200	silver perch	Rowland (1995a)
	20–175	freshwater species	DWAf (1996)
Brackish water fish	50–200	barramundi	Curtis pers comm
Freshwater crustaceans	>100	crayfish	De la Bretonne (1969)
	50–200	crayfish and shrimp	Lee & Wickins (1992)
	50–400	yabbies	Wingfield pers comm
	50–300	marron	Wingfield pers comm
	>50	crayfish	Boyd (1990)
Marine crustaceans	160–400	black tiger prawn	Lee & Wickins (1992)

NC: Not of concern

8. pH

The term pH refers to the hydrogen ion (H^+) concentration in water; more generally, pH refers to how acidic or basic a water is. pH is interdependent with a number of other water quality constituents, including carbon dioxide, alkalinity and hardness. It is known to influence the toxicity of hydrogen sulphide, cyanides and heavy metals, as well as having an indirect effect on ammonia levels; un-ionised NH_3 increases with pH (Klontz 1993).

In aquaculture, low pH is often a consequence of sulfuric acid formation by the oxidation of sulphide-containing sediments, as commonly occurs where iron pyrite is present (Lawson 1995, Zweig et al. 1999). The EIFAC (1969) noted that acidification of highly alkaline water can increase the free carbon dioxide concentration, resulting in CO_2 toxicity rather than pH imbalance. In addition, acid water tends to dissolve metals more readily. For example, aluminium concentrations are high in acid waters (Haines 1981). According to Nowak (1996), acidification of estuarine tributaries due to drainage of acid sulfate soils (which have

pH <3.5) can cause low pH by providing a long term source of dilute sulphuric acid and dissolved metals (iron, aluminium and manganese). High pH in aquaculture is commonly a result of excess photosynthesis in waters with high alkalinity and low calcium hardness (Zweig et al. 1999).

pH can indirectly affect aquaculture species through its effect on other chemical parameters (Zweig et al. 1999). For example, low pH reduces the amount of dissolved inorganic phosphorus and CO₂ available for phytoplankton photosynthesis. In addition, low pH can result in the solubilisation of potentially toxic metals from the sediments, while at high pH, the toxic form of ammonia becomes more prevalent. Phosphate, which is commonly added as a fertiliser, can precipitate at high pH (Boyd 1990, Zweig et al. 1999).

However, species tolerances can vary. For example, in comparison with cyprinids (especially carp and tench), salmonids are more vulnerable to high pH and more resistant to low pH (Svobodova et al. 1993).

During transfers, animals should be acclimatised slowly to waters of different pH.

Guideline notes

Meade (1989) recommended that pH be maintained at between 6.5 and 8.0 for all aquaculture species.

In freshwater, pH can change quickly due to the amount of carbon dioxide added or removed during plant growth. In culture systems, particularly recirculation systems, the pH may be reduced (more acidic) by the production of metabolites. Buffering is, therefore, important in such systems.

Most estuarine and freshwater species are tolerant of a relatively wide range of environmental pH (Tomasso 1993), around pH 5.5 to pH 8 (Schlotfeldt & Alderman 1995). Swingle (1969) claims that the desirable range for warmwater pond fish is 6.5 to 9.0 (measured at daybreak [Ellis 1937]). A range of 5.0 to 9.0 was considered safe by the European Inland Fisheries Advisory Commission (EIFAC 1969). Above and below this range results in slow growth and then death. However, these ranges may be too high when considering interactions with other environmental variables or during certain stages of the life cycle. For example, in water containing high levels of ammonia, a pH of 9.0 will cause a high percentage of the ammonia to exist in the toxic un-ionised form of ammonia (Emerson et al. 1975). This is a problem in poorly buffered pond water during the late afternoon hours when the natural pH rhythm peaks (pH increases through the day as photosynthesis increases). In fact pH has been known to exceed 10 to 11 in poorly buffered ponds in the late afternoon.

Therefore, the recommended guideline (table 9.4.10) is that pH be maintained at between 5.5 and 9.0 for freshwater.

However, seawater, in general, resists changes in the pH values (Poxton & Allhouse 1982) and usually has a pH around 8.2 (Walker 1994). The alkalinity of the seawater provides greater protection against carbon dioxide build-up, while in the well-buffered brackish water the pH is normally between 6.5 and 9.0 (Boyd 1989). For saltwater species the range of 6.0 to 9.0 pH units is recommended as the guideline (table 9.4.10).

It should be noted that pH can change by the hour as a function of photosynthesis which removes carbon dioxide. This is particularly the case in pond-based culture systems. Therefore, readings should be taken over the daylight hours to gain a better appreciation of the pH levels.

See also discussions under Alkalinity (9.4.2.1/1) and Temperature (9.4.2.1/11).

Table 9.4.10 Summary of the recommended water quality guidelines for pH

Group	Guideline (pH units)	Comments	Reference
Recommended guidelines	5.5–9.0	freshwater	Professional judgement
	6.0–9.0	saltwater	Professional judgement
General	5.5–8.0 6.5–8.5	freshwater all aquaculture species	Schlottfeldt & Alderman (1995) Meade (1989)
Freshwater fish	6.5–9.0	silver perch, rainbow trout	Rowland (1995a), CCME
	7–7.5	aquaculture species	(1993) DWAF (1996)
	7–7.5	rainbow trout	Holliman (1993)
	6.5–9.0 5.0–9.0	warmwater pond fish	Swingle (1969) EIFAC (1969)
Marine fish	6.7–8.6	optimal	Pillay (1990)
Brackish water fish	6.7–8.6	optimal	Pillay (1990)
Freshwater crustaceans	6.5–8.5	freshwater crustaceans	various
Marine crustaceans	7.8–8.3	prawns and crabs	Lee & Wickins (1992)
	6–9	prawns	Boyd (1989)

9. Salinity (total dissolved solids)

Total dissolved solids is a composite measure of the total amount of material dissolved in water. This parameter can be represented in three ways: as total dissolved solids (TDS), as salinity or as conductivity. TDS and salinity are both measures of the mass of solutes in water; however, they differ in the components they measure (salinity only measures dissolved inorganic content whereas TDS is the mass of dissolved inorganic and organic compounds in water).

Salinity is the main measure used in aquaculture, as it influences the water and salt balance (osmoregulation) of aquatic animals. It usually is expressed in mg/L, but in aquaculture it is commonly expressed in parts per thousand (ppt or ‰). Most inland waters contain 0.05 to 1.0 ppt salinity, although in arid regions and with artesian water the salinity can be very high. Estuarine waters may range from 0.5 to more than 30 ppt often depending on the depth of the sample; marine waters range between 30.0 to 40.0 ppt, brine or hypersaline waters display salinities above 40 ppt.

As with pH (Section 9.4.2.1/8) salinity can vary significantly over a short time period (e.g. 5–6 hours), particularly in or near estuaries. It can also vary significantly with various weather events, particularly precipitation in the catchment of the water source. Therefore readings need to be made over the appropriate time periods (daily and seasonal).

Salinity directly affects the levels of dissolved oxygen: the higher the salinity, the lower the dissolved oxygen levels at a given water temperature.

Like temperature, salinity is an important limiting factor in the distribution of many aquatic animals. Diadromous fish (e.g. barramundi) and anadromous fish (e.g. salmonids) can move between full-strength seawater and freshwater as part of their reproductive activities. Brackish water species are more tolerant of rapid changes in salinity; however, even they can be limited in their distribution by salinity gradients. Euryhaline animals can tolerate wide changes in salinity, while those tolerating only limited ranges are referred to as stenohaline.

Some animals (e.g. fish) are osmoregulators and are able to regulate the concentration of their body salts despite changes in the salinity of their environment, while others (e.g. bivalves) are osmoconformers and alter their salt levels to that of the environment.

Salinity requirements can vary for particular species depending on their life cycle stage. Salinity also affects the temperature requirements of some species, although there is a lack of understanding of temperature-salinity interactions and the effects of changing the ionic ratios for many species (Tomasso 1993).

Freshwater organisms have body fluids more concentrated in ions than the surrounding water, meaning that they are hypersaline or hypertonic to the environment. These animals tend to accumulate water which they must excrete while retaining ions. Saltwater species have body fluids more dilute in ions than the surrounding water; they are hyposaline or hypotonic to their environment. They must excrete ions and uptake water continually. Outside of their natural salinity ranges, aquatic animals must expend considerable energy for osmoregulation at the expense of other processes, such as growth.

Many brackish water and marine animals can adjust to changes in salinity if the change is made gradually (i.e. no more than 10% change in an hour).

Guideline notes

Salinity tolerance varies significantly between species and some species have wider tolerances than others (particularly those which live in brackish water. However, the recommendations of Lawson (1995) are used for the recommended guidelines (table 9.4.11)

See also discussions under Suspended solids and turbidity (9.4.2.1/10).

Table 9.4.11 Summary of the recommended water quality guidelines for salinity

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	<3	freshwater	Lawson (1995)
	3–35	brackish water	Lawson (1995)
	33–37	saltwater	Lawson (1995)
General	not applicable	See species requirements	
Freshwater fish	<3		Lawson (1995)
Marine fish	>30		Swindlehurst pers comm
	30–40		Zweig et al. (1999)
	33–37		Lawson (1995)
Brackish water fish	3–35		Lawson (1995)
Freshwater crustaceans	<6	best for yabbies	Mills & Geddes (1980)
	<7	best for marron	Morrissy (1976)
Marine crustaceans	15–30	<i>P. monodon</i>	Lee & Wickins (1992)
	8–35	crabs and lobsters	Lee & Wickins (1992)
Edible bivalves	27–39	Highest survival for Sydney rock oyster larvae	Nell & Holliday (1988)
	20–40	Good growth in Sydney rock oyster adults	Nell & Holliday (1988)
	19–27	Best for Pacific rock oyster larvae	Nell & Holliday (1988)
	15–45	Good growth in Pacific oyster adults	Nell & Holliday (1988)
Non edible bivalves	>30	pearl oysters	FAO/UNDP (1991)
	20–35	<i>Pinctada fucata</i>	Namaguchi (1994)
	30–34	<i>Pinctada maxima</i> spat	Southgate pers comm
	30–35	<i>Pinctada margaritifera</i> spat	Southgate pers comm
Gastropods	>25	abalone	Hahn (1989)

10. Suspended solids and turbidity

There are three basic types of suspended solids:

- phytoplankton, zooplankton and bacterial blooms
- suspended organic and humic acids
- suspension of silt and clay particles

All influence the level of turbidity (turbidity increases with suspended solids) and scatter light, restricting penetration into water. In aquaculture ponds, less light penetrating to the bottom inhibits growth of troublesome filamentous algae and aquatic weeds.

Particularly in aquaculture ponds, the biological turbidity can vary significantly due to a number of management strategies (refer to Boyd 1989 and 1990 for further discussion). This turbidity is often measured in centimetres using a secchi disc (i.e. it is the distance (cm) into the water at which a black and white disc become visible to the naked eye). For silver perch, the preferred secchi disc reading is 30 to 45 cm (Rowland 1995a), <200 cm for snapper (Ogburn 1996), <30 cm for barramundi, 30 to 40 cm for freshwater crayfish (O'Sullivan 1992), and <20 cm for prawns (Anderson 1993).

Typically, if the secchi disk reading is below 10 cm water turbidity is excessive. If turbidity is due to the presence of phytoplankton, there is likely to be a problem with dissolved oxygen concentrations when the light level decreases below the photosynthetic compensation level. Conversely, if turbidity is due to silt/clay or organic matter, planktonic productivity will be low.

Duchrow and Everhart (1971) pointed out that the main concern with regard to the protection of sessile benthic aquatic fauna and flora is not the suspended particles (turbidity) per se, but the amount of solids in suspension that potentially can settle out (settleable or suspended solids).

The measure for suspended solids (sometimes called non filterable residue or NFR) is measured in mg/L. The opposite is filterable residue or total dissolved solids (refer to Salinity, Section 4.4.4.3/1 for more information).

Suspended solids can cause gill irritations and tissue damage, which increases the stress levels of aquatic animals. Cold water fish have been killed upon exposure for 3 to 4 weeks to 500 to 1000 mg/L of suspended solids (Alabaster & Lloyd 1982). Turbid waters can also shield food organisms and clog filters (Zweig et al. 1999). Although sediment accumulation may be troublesome, the oxygen demand of the sediment and of particulate and dissolved organic matter has more serious consequences (Klontz 1993).

The practice of mechanical aeration tends to create water currents which maintain soil particles in suspension and perpetuates the turbidity of the pond (Boyd 1990). Problems of off-flavours in fish and crayfish are less common in turbid ponds (Walker 1994) (except where algae cause the turbidity), although the blue-green algae *Microcystis* is known to exist in waters with high clay turbidity.

Guideline notes

The effect of this criteria varies considerably between species. Meade (1989) recommended a level below 80 mg/L for aquaculture species.

Klontz (1993) stated that levels below 80 mg/L were quite innocuous for freshwater fish. Alabaster and Lloyd (1982) recommended a level below 80 mg/L for freshwater aquaculture, however, some species (e.g. rainbow trout) require lower levels of suspended solids so a median level of <40 mg/L is recommended as the guideline (table 9.4.12).

Marine species (e.g. snapper) are generally less tolerant, so the recommended guideline is <10 mg/L based on the lowest species recommendation i.e. snapper (table 9.4.12). However, as brackish water species (e.g. prawns and barramundi) can tolerate higher levels the recommended guideline for such waters is <75 mg/L.

Table 9.4.12 Summary of the recommended water quality guidelines for suspended solids and turbidity

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	<40	freshwater	Professional judgement
	<10	saltwater	Professional judgement
	<75	brackish water	Professional judgement
General	<80	freshwater	Alabaster & Lloyd (1982)
	<80	all aquaculture species	Meade (1989)
Freshwater fish	<80		Klontz (1993)
	<25	rainbow trout	SECL (1983), Lloyd (1992)
Marine fish	<25	Atlantic salmon	Klontz (1993)
	<10	snapper	Ogburn (1996)
Brackish water fish	<75	barramundi	Swindlehurst pers comm
Marine crustaceans	<14	crabs/lobsters	Lee & Wickins (1992)
	<75	black tiger prawns	Swindlehurst pers comm
Non edible bivalves	<25	pearl oysters	FAO/UNDP (1991)
	<40	<i>Pinctada maxima</i> spat	Mills pers comm

11. Temperature

Water temperature is a fundamental parameter that affects the health of aquatic organisms. These organisms all have specific temperature ranges within which they can live normally. The natural temperature range encountered in specific regions of the sea is small in comparison with that observed in freshwater, particularly impounded surface waters.

The availability of oxygen is directly affected by the temperature of a water body (salinity and the rate of oxidation of organic matter also affect oxygen availability). Water temperature affects metabolism (metabolic rate), feed intake, growth, reproduction, physiological processes (affects the function of enzymes), disease immunity, movements and respiration rate. It also influences the susceptibility to potential toxic compounds and ammonia levels (Klontz 1993), as well as the bioaccumulation and detoxification (Zweig et al. 1999) and solubility of fertilisers.

Water temperature tolerances are specific to each species and are difficult to group into categories. Rowland (1986) pointed out that many species suitable for aquaculture will survive and reproduce over a wide temperature range, but the optimum temperature range for maximum growth is more narrow. For example, a species might tolerate temperatures of 5 to 36°C, but the range for maximum growth might be from 25 to 30°C. It is useful to note that best growth often occurs when the water is close to lethal temperatures; care is required to prevent losses if temperatures rise.

In aquaculture, it is seldom economical to cool or heat large volumes of water. Sites should be selected in geographic regions that provide an ambient temperature conducive to the growth of market size products within a reasonable period of time (Lawson 1995). It is imperative that the temperature never deviates beyond lethal limits (Zweig et al. 1999). Therefore, species which exhibit maximum growth rates at prevailing water temperatures usually are selected for a particular location (Lawson 1995, Boyd 1999):

Tropical/subtropical	grow well above 26–28°C
Warm water	grow best at 20–28°C
Cool water	grow well between 15 and 20°C
Cold water	grow best below 15°C

If animals are transferred between waters with a greater temperature difference than 3 to 4°C, the sudden changes in metabolism may cause thermal shock and even death (Boyd 1990). Temperature change of 0.2°C/min usually can be tolerated for overall changes below 2°C over a one hour period (ANZECC 1992).

Tomasso (1993) noted that the temperature requirements of a given (fish) species will vary with several factors:

- estuarine species may exhibit more or less tolerance of extreme temperatures depending on the concentration of dissolved solids in their environment;
- acclimation to extreme temperature can occur in some species;
- differing stages of the life cycle may have different temperature optima;
- complex physiological changes occurring during reproduction very often are dependent on absolute temperatures, changing temperatures and interaction with other abiotic factors, such as photoperiod.

Guideline notes

This general water quality criteria varies significantly between species (see Lawson 1995 and Zweig et al. 1999 for species summaries). Consequently it is recommended that changes to water temperature be kept below 2°C over a one hour period (table 9.4.13) as provided by ANZECC (1992).

See also discussions under BOD (9.4.2.1/2) and Dissolved oxygen (9.4.2.1/5).

Table 9.4.13 Summary of the recommended water quality guidelines for temperature

Group	Guideline	Comments	Reference
Recommended guideline	<2.0°C change	over 1 hour	ANZECC (1992)

9.4.2.2 Inorganic toxicants (heavy metals and others)

A number of chemicals can occur in surface waters as a result of human activities. These can be of inorganic (this Section) or organic (Section 9.4.2.3) origin.

A wide range of heavy metals can be a problem in freshwater, brackish water and inshore marine aquaculture, especially in areas of human habitation (pollution). Trace quantities of metals are present in natural waters; however, their concentrations are generally greater where pollution from industrial processes (ore mining and processing, smelting plants, rolling sheet metal mills, textile and leather industries) as well as exhaust gases of motor vehicles and burning of other fossil fuels occurs. The metals of greatest concern to fisheries (and aquaculture) include aluminium, arsenic, cadmium, chromium, copper, iron, lead, mercury, nickel and zinc (Svobodova et al. 1993). Other inorganic toxicants include ammonia, chlorine, cyanide, fluoride, hydrogen sulfide, nitrite, nitrate and phosphates.

Increasing hardness (9.4.2.1/7) reduces the uptake and toxicity of several metals, including cadmium, chromium (III), copper, lead, nickel and zinc, to freshwater organisms. Other physio-chemical parameters, especially pH and redox potential, will also influence metal bio-availability (refer to equations in Section 3.4.3.2 of Volume 1).

Speciation of metals is important in determining toxicity to aquatic organisms, as this influences their bio-availability. Water quality guidelines for metals in aquatic ecosystems have typically been based on total concentrations, yet it is now well established that bio-availability, i.e. the ability to penetrate a biological cell membrane, and toxicity of metals to aquatic organisms is critically dependent on the chemical form or speciation of these metals.

Most studies of the toxicity of heavy metals to fish and other aquatic organisms have shown that the free (hydrated) metal ion is the most toxic form, and that toxicity is related to the activity of the free metal ion rather than to total metal concentration (Florence & Batley 1988). Their toxicity also can be affected by pH, hardness, alkalinity, dissolved oxygen, temperature and turbidity (SECL 1983). Duration of exposure, interaction with other toxic agents and species can affect the biological response to these toxic metals significantly, e.g. mercury and methane give rise to methyl mercury.

A discussion of speciation considerations has been provided in Section 8.3.5.16 of Volume 2. It is only noted here that guidelines based on total concentrations may be over protective, since only a fraction of the total concentration will generally be bio-available, especially in samples containing appreciable concentrations of particulate matter. Measurement of the bio-available metal is required, but this is not a trivial exercise, and a hierarchy of measurements of increasing complexity must be prescribed.

The mechanisms of metal toxicity to fish are varied, although many act as enzyme poisons. Therefore, it is difficult to assess the probable effect of a measured concentration of a metal. In pond water heavy metals can be adsorbed onto clay particles and chelated by organic matter so that they remain in solution but may not have an adverse effect on fish or crustaceans (Boyd 1990). The toxicity of heavy metals is related primarily to the dissolved, ionic form of the metal, e.g. Cu^{2+} or Zn^{2+} , rather than to absorbed, chelated or complexed forms (Boyd 1989). Svobodova et al. (1993) note that the toxic action of metals is particularly pronounced in the early stages of development of the fish.

1. Aluminium

Aluminium (Al) is amongst the most abundant naturally occurring metals. The toxicity of aluminium varies with pH and other physico-chemical properties of water. Aluminium is soluble at pH values below 6.0; a number of chemical species can be formed, the most toxic occurring at pH 5.2 to 5.8. At higher pH values, an aluminium hydroxide precipitate is formed, which can flocculate in water. According to Svobodova et al. (1993), the fully flocculated hydroxide has a low toxicity, similar to that of suspended solids in general.

In freshwater, aluminium can cause problems for aquarium fish if town supply water is used.

The speciation and bio-availability of aluminium is discussed in Section 8.3.7.

Guideline notes

At pH greater than 6.5, an aluminium guideline of less than 0.03 mg/L is recommended as the guideline (DWAF 1996), while at lower pH the tolerance is reduced so a level of less than 0.01 mg/L is recommended. Meade (1989) suggested that for saltwater, aluminium should remain below 0.01 mg/L and this is used as the recommended guideline (table 9.4.14).

Table 9.4.14 Summary of the recommended water quality guidelines for aluminium

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	<0.03	freshwater at pH >6.5	DWAF (1996)
	<0.01	freshwater at pH <6.5	DWAF (1996)
	<0.01	saltwater	Meade (1989)
Freshwater fish	0.05	rainbow trout	Svobodova et al. (1993)
	0.003	rainbow trout	Holliman (1993)
	0.1	freshwater species	Schlotfeldt & Alderman (1995)

2. Ammonia (and total ammonia nitrogen, TAN)

Ammonia ($\text{NH}_3/\text{NH}_4^+$) reaches aquaculture waters as a by-product of metabolism (respiration) by animals and by decomposition of organic wastes by bacteria. Ammonia is one of the forms of the breakdown of nitrogenous waste products (excreted from aquatic organisms); the other forms produced under aerobic conditions by nitrifying bacteria are the toxic nitrite (NO_2^- -N) and relatively harmless nitrate (NO_3^- -N).

Ammonia concentration is an indicator of the pond's water quality: the greater the ammonia the poorer the water quality (Walker 1994). Most ammonia problems occur under intensive conditions where high feeding rates combined with low dissolved oxygen levels result in significantly higher ammonia levels. However, nitrate levels also need to be considered to determine the level of nitrification that is occurring in the culture water (Section 9.4.2.2/18).

The accumulation of ammonia in the water is known to be one of the major causes of functional and structural disorders in aquaculture (Poxton & Allhouse 1982). Ammonia can be a major problem for recirculating tank systems than for ponds because they do not often contain phytoplankton and macrophytes to assimilate ammonia unless an adequately sized nitrifying filter is installed (Zweig et al. 1999).

The major source of ammonia in aquaculture waters is the direct excretion of ammonia by molluscs, fish and crustaceans. In-pond sediments can also be a major source of ammonia (Burford, pers. comm. 1999, Hargraves, pers. comm. 1998). However, Svobodova et al. (1993) state that ammonia pollution may also be a result of domestic sewage, agricultural wastes or the reduction of nitrates and nitrites by bacteria in anoxic waters, or of inorganic origin, such as industrial effluents from gas works, coking plants and power generating stations.

Ammonia toxicity is greatly affected by the water chemistry. The toxicity of total ammonia nitrogen (TAN: being the sum of ammonium [NH_4^+] + unionised ammonia [NH_3]) depends on the fraction that is unionised (i.e. NH_3), since this is the most toxic form. The ionised form, NH_4^+ , may also be toxic, but only at very high concentrations (Boyd 1990). Ionised and unionised ammonia exist at an equilibrium that depends on pH, temperature and salinity. Ammonia is usually measured as TAN, thus, the above modifying factors must be known to calculate the concentration of unionised ammonia (Zweig et al. 1999). According to Svobodova et al. (1993), the lower the oxygen concentration in water, the greater the toxicity of ammonia.

SECL (1983) noted that life stage, carbon dioxide concentrations, ionic strength and alkalinity all affect ammonia toxicity. Other factors are discussed by Zweig et al. (1999).

At lower temperatures and lower pHs, more of the relatively non-toxic ammonium is present. Ammonia is 30% less toxic in seawater than freshwater at the same pH and is also less at higher dissolved oxygen concentrations (Walker 1994).

High ammonia concentrations affect bodily functions and can damage gills. Chronic exposure to ammonia increases susceptibility to disease and reduces growth (Colt & Armstrong 1979).

Ammonia is more toxic when dissolved oxygen concentrations are low; however, the toxicity decreases with increasing oxygen levels. Thus, the effect is probably nullified in fish ponds because carbon dioxide concentrations are usually high when dissolved oxygen levels are low.

A combination of high total ammonia and high pH can cause ammonia toxicity in fish and crustaceans.

Guideline notes

Safe environmental ammonia concentrations are difficult to establish because of species differences and the complexity of evaluating low-level exposures (Tomasso 1993). As there is little consensus regarding permissible levels of ammonia (e.g. proposed guideline levels for marine crustaceans vary by a factor of ten; see table 9.4.15), Zweig et al. (1999) suggest it is best to be conservative.

Schlotfeldt and Alderman (1995) suggested that for freshwater aquaculture species at pH above 8.5, an ammonium (NH₄) level <0.05 mg/L should be used whilst below pH 8.5 it should be <1.0 mg/L.

Coche (1981) suggested a level below 0.1 mg/L for farm fish, molluscs and crustaceans. Meade (1989) suggested that un-ionised ammonia levels should be maintained at <0.02 mg/L. However, according to DWAF (1996), some species have lower un-ionised ammonia requirements depending on pH and temperature:

- <0.025 mg/L cold-water freshwater farm fish at pH >8.0, at lower pH to 0.0 mg/L;
- 0.0–0.3 mg/L warm-water freshwater farm fish.

Therefore, for freshwater species, the more conservative levels suggested by DWAF (1996) are used as the recommended guidelines (table 9.4.15) whilst for saltwater species a higher level of <0.1 mg/L is used due to the reduced toxicity of ammonia in seawater.

The suggestion of Meade (1989) for a level for TAN at <1.0 mg/L for aquaculture species is used as the recommended guideline (table 9.4.15).

See also the discussions for Nitrate (9.4.2.2/18) and Nitrite (9.4.2.2/19).

3. Arsenic

The main sources of arsenic pollution in surface waters include byproducts of mineral ore processing, tanneries and dyestuff production plants, and the burning of crude oil and coal. Arsenic is commonly used in insecticides, herbicides and wood preservatives (Zweig et al. 1999). There are also natural groundwater sources of arsenic, derived from arsenic ores and volcanic activity that can reach concentrations sufficiently high to cause human health problems (Zweig et al. 1999). It is able to accumulate in large quantities in the sediments of ponds and in aquatic organisms (Svobodova et al. 1993).

Typically, the concentration of arsenic in freshwater is less than 1 µg/L and in seawater 4 µg/L (DWAF 1996).

According to Zweig et al. (1999) arsenic speciation in water is complex. It can exist in four oxidation states depending on whether it is in oxidising or reducing conditions. Arsenic binds strongly to particulate matter (a dominant form of arsenic in natural waters), can co-precipitate with iron oxides, and under reducing conditions, can precipitate as arsenic sulfide or elemental arsenic. Arsenic also forms methylated species through microbial action (Zweig et al. 1999).

Table 9.4.15 Summary of the recommended water quality guidelines for unionised ammonia and TAN

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	<0.025	pH >8.0 cold freshwater	DWAF (1996)
	0.0	pH <8.0 cold freshwater	DWAF (1996)
	<0.3	warm freshwater	DWAF (1996)
	<0.1	saltwater	Professional judgement
	<1.0	TAN all species	Meade (1989)
General	<0.1	farm species	Coche (1981)
	<0.02	aquaculture species	Meade (1989)
	<1.0	TAN all species	Meade (1989)
Freshwater fish	<0.05	pH >8.5	Schlotfeldt & Alderman (1995)
	<1.0	pH <8.5	Schlotfeldt & Alderman (1995)
	<0.025	pH >8.0 coldwater	DWAF (1996)
	<0.3	warmwater fish	DWAF (1996)
	<0.1	silver perch	Rowland (1995a)
	<0.02	rainbow trout	Lloyd (1992)
	<1.0	freshwater species	Lloyd (1992)
	<1.0	TAN for freshwater fish	Lawson (1995)
Marine fish	<0.01	flounder	Hutchinson et al. (1992)
	0.0125	salmonids	Shepherd & Bromage (1988)
	<0.3	bream	Wajsbrodt et al. (1993)
	<0.01	safe concentration	Huguenin & Colt (1989)
Brackish water fish	<0.1	barramundi	Rimmer (1995)
		many farm species	Boyd (1990)
Freshwater crustaceans	<0.1		Lee & Wickins (1992) Wingfield pers comm
Marine crustaceans	<0.1	all penaeids	Chin & Chen (1987)
	0.13	black tiger prawn	Chien (1992)
	<0.4	prawns	Boyd & Fast (1992)
	4.1	juvenile black tiger prawns	Allen et al. (1990)
Non edible bivalves	<0.001		Hahn (1989)
Gastropods	<0.003	abalone	Fallu (1991)

As a rule, arsenic occurs in the oxidation state V, but some of it also may be present in non-stable forms (i.e. in the oxidation state III) which can rapidly be absorbed into fish and are more toxic than those V forms. As with mercury (see 9.4.2.2/15) biological (particularly bacterial) activity may lead to the formation of organic methyl derivatives of arsenic (Svobodova et al. 1993).

To a large extent, pH and redox potential determine the inorganic arsenic species present in the aquatic environment. Metabolically, arsenic interacts with many elements, among them selenium and iodine (DWAF 1996). The speciation and bioavailability of arsenic are discussed in more detail in Section 8.3.7.

Information on the toxicity of arsenic to aquatic species is limited. Existing information indicates that arsenic is relatively non-toxic to aquatic organisms, with concentrations of ~1 mg/L required to cause mortality (Zweig et al. 1999). However, arsenic is more toxic to phytoplankton, with growth being affected at levels as low as five times the background concentration (Zweig et al. 1999).

Guideline notes

Meade (1989) suggested arsenic levels remain below <0.05 mg/L for both freshwater and marine species. DWAF (1996) also recommended a level of <0.05 mg/L for freshwaters. However, Eisler (1988a) recommended a higher level (<0.19 mg/L) for freshwater life than for marine species (0.036 mg/L), suggesting that freshwater species may be more tolerant of

arsenic than saltwater species. The dataset does not provide sufficient evidence to test this hypothesis further.

Thus, the values suggested by DWAF (1996) and Meade (1989) are used as the recommended guidelines (table 9.4.16).

Table 9.4.16 Summary of the recommended water quality guidelines for arsenic

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	<0.05	freshwater & saltwater	DWAF (1996), Meade (1989)
General	<0.05	freshwater	DWAF (1996)
	<0.05	freshwater & saltwater	Meade (1989)
	<0.19	freshwater	Eisler (1988a)
	<0.036	saltwater	Eisler (1988a)
Freshwater fish	<0.05	freshwater species	Schlotfeldt & Alderman (1995)
	<1.0	salmonid hatchery	SECL (1983)
Edible bivalves	0.03	1/100th of 48 hr EC ₅₀ blue mussel larvae	Seed & Suchanek (1992)

4. Cadmium

Cadmium (Cd) is a highly toxic metal that is used in a variety of industrial processes including electroplating, nickel plating, smelting, engraving and battery manufacturing (Zweig et al. 1999). Inorganic (e.g. phosphate) fertilisers, reclaimed sewage sludge, municipal sewage effluents, and zinc (and other) mine tailings are also important sources of cadmium contamination (Zweig et al. 1999). Cadmium is usually associated with zinc in surface waters, but at much lower concentrations (Svobodova et al. 1993). The predominant form in the environment is the free ion (Cd²⁺), although it will also complex with organic matter and particulates (Dojlido & Best 1993). Unlike mercury, it does not form organometallic complexes. In anoxic sediments, cadmium will precipitate as cadmium sulfide (Zweig et al. 1999). Background levels of cadmium in natural freshwaters are usually very low, generally ranging from 0.0 to 0.13 ppb (0.00013 mg/L), while saline water levels are typically less than 0.2 ppb in estuaries (<2.0 ppb in estuarine sediments) and less than 0.15 ppb in coastal areas (<1.5 ppb in marine sediments) (Zweig et al. 1999). The speciation and bioavailability of cadmium is discussed in more detail in Section 8.3.7.

According to Svobodova et al. (1993), of the dissolved forms, those which may be toxic to fish include the free ion and various inorganic and organic complex ions. Cadmium is of particular concern to aquaculture as it bioaccumulates (DWAF 1996). Apart from an acute toxic action which is similar to that of other toxic metals (damage to the nervous system), very small concentrations of cadmium may produce specific effects after a long exposure period, especially on the reproductive organs (Svobodova et al. 1993).

Cadmium toxicity is reduced with increasing levels of calcium and magnesium in the water (i.e. the harder the water the lower the toxicity). A similar relationship exists between cadmium and alkalinity. At high water temperatures, cadmium levels increase and fish survival decreases under low dissolved oxygen conditions. Additive (synergistic) effects have been found with cadmium and copper and cadmium and mercury, while cadmium toxicity is lowered in the presence of sub-lethal concentrations of zinc (DWAF 1996).

Guideline notes

The recommended guidelines for freshwater species vary with hardness as per DWAF (1996):

- at hardness 0–60 mg CaCO₃/L the guideline should be 0.0002 mg/L
- at hardness 60–120 mg CaCO₃/L the guideline should be 0.0008 mg/L
- at hardness 120–180 mg CaCO₃/L the guideline should be 0.0013 mg/L
- at hardness >180 mg CaCO₃/L the guideline should be 0.0018 mg/L.

These are more conservative than those suggested by Schlotfeldt and Alderman (1995).

The paucity of information on saltwater species makes the recommendation of guidelines difficult, however, Meade (1989) recommended a guideline of 0.005 mg/L for hardness >100 mg CaCO₃/L, and 0.0005 mg/L for hardness <100 mg CaCO₃/L.

To remain conservative, the suggestions by DWAF (1996) and Meade (1989) are used as the recommended guidelines (table 9.4.17). The values should be lowered if dissolved oxygen concentration is low or other metal toxicants are present.

Table 9.4.17 Summary of the recommended water quality guidelines for cadmium

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	<0.0002–0.0018 <0.005–0.0005	freshwater (see above notes on hardness) saltwater and freshwater (see above notes on hardness)	DWAF (1996) Meade (1989)
General	<0.0002–0.0018 <0.005–0.0005	freshwater (see above notes on hardness) saltwater and freshwater (see above notes on hardness)	DWAF (1996) Meade (1989)
Freshwater fish	<0.0002 <0.001 <0.003 <0.1 0.004 0.012	salmonids rainbow trout silver perch no effect limit for salmonids all freshwater aquaculture species in softwater all freshwater aquaculture species in hard water	Schreckenbach (1982), Svobodova et al. (1993) Holliman (1993) Rowland (1995a) Klontz (1993) Schlotfeldt & Alderman (1995) Schlotfeldt & Alderman (1995)
Freshwater crustaceans	<0.15 <0.0011		Wingfield pers comm US EPA (1986)
Marine crustaceans	<0.15 <0.053 <0.0093	black tiger prawn black tiger prawn marine crustaceans	Chen (1985) Smith (1996) US EPA (1996)
Molluscs	<0.0005	Regardless of hardness	Zweig et al. (1999)
Edible bivalves	<0.01	1/10th of level for 50% shell growth reduction in blue mussel juveniles	Seed & Suchanek (1992)

5. Chlorine

Chlorine (Cl) is a gas. Effluents containing chlorine can be discharged from municipal and agricultural water treatment plants, swimming pools, dairies and from various industrial plants. Chlorine is also used for destroying biofouling in the water cooling systems of power stations. In the early 1970s, failures of natural sets of Pacific oysters in the Tamar estuary of Tasmania were allegedly due to large quantities of chlorine which were used in the hydro-electric plant. Low concentration of chlorine can be absorbed naturally by organic matter in the water and in sediments (Svobodova et al. 1993).

Chlorine seldom occurs in nature, but is usually found as its anion, chloride. The chlorides of alkaline and alkaline earth metals are all highly soluble in water, e.g. sodium, potassium, calcium and magnesium. Whilst chlorine is a major constituent of seawater, it is in the stable form NaCl, so while there are usually 19 000 mg/L chloride as ionised salts in seawater, this form represents no danger. Chlorides are of concern in water supplies used for aquaculture because the anions of chloride are essential for osmotic, ionic and water balance in all fishes (DWAF 1996). Chlorine commonly reacts to form toxic chloramines in solution (Zweig et al. 1999).

Both free and combined chlorine residuals are extremely toxic to fish (Tompkins & Tsai 1976). If measurable concentrations (e.g. <0.08 mg/L) of residuals are present in the water, the water should not be considered safe for holding fish. Boyd (1990) noted that actual concentration of chlorine in city water supplies may be much greater than 1 mg/L.

The toxicity of the chlorine is increased with increasing water temperatures, while toxicity decreases with increasing pH.

Ammonia can combine readily with free chlorine to form the very toxic chloramines. This is particularly a problem in enclosed systems for aquarium fish using city water supplies.

Active chlorine may affect specific parts of the fish (e.g. the skins and gills) or the whole body (i.e. when chlorine is absorbed into the blood). The systemic effect manifests itself mainly as nervous disorders (Svobodova et al. 1993).

Prawn farmers are known to use post-harvest chlorination in an attempt to eliminate potential pathogens. Since the chlorinated water is exposed to sunlight for some time, the chlorine rapidly breaks down into its non-toxic derivatives during this procedure.

Guideline notes

Meade (1989) suggested levels below 0.003 mg/L for all aquaculture species, this was supported by Pillay (1990) who suggested a level less than 0.003 mg/L for all farmed fish species. Svobodova et al. (1993) consider that prolonged exposure to active chlorine concentrations above 0.04 mg/L will be toxic to the majority of fish species, whilst Schlotfeldt and Alderman (1995) suggested the range from 0.01 to 0.03 mg/L for freshwater species (these two suggestions are an order of magnitude higher than the first two suggestions).

The lower limit (Meade 1989) is recommended as the guideline for freshwater and saltwater species (table 9.4.18).

6. Chromium

Chromium (Cr) is mostly used in plating and chrome alloy production, but is also found in pigments, paints, ceramics, textile dyes, fungicides, fireproof bricks and catalysts (Zweig et al. 1999). Chromate compounds are also used for corrosion control in heating and cooling systems (Dojlido & Best 1993).

Table 9.4.18 Summary of the recommended water quality guidelines for chlorine

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	<0.003	freshwater & saltwater	Meade (1989)
General	<0.003	all aquaculture species	Meade (1989)
	<0.01–0.03	freshwater species	Schlotfeldt & Alderman (1995)
	<0.04	most fish species	Svobodova et al. (1993)
Freshwater fish	<0.08	general	Tompkins & Tsai (1976)
	<0.03	silver perch	Rowland (1995a)
	<0.002	rainbow trout	Forteach pers comm
	<0.002	salmonid aquaculture	DWAF (1996)
	<0.003	farmed fish	Pillay (1990)
Marine fish	<0.04	optimal	Svobodova et al. (1993)
	<0.003	farmed fish	Pillay (1990)
Brackish water fish	<0.03	barramundi	Curtis pers comm
Freshwater crustaceans	<0.03	freshwater crayfish	Wingfield pers comm

NC: Not of concern

Under reducing conditions chromium is present as the free trivalent ion (Cr^{3+}), while in oxidising conditions such as those commonly found in aquaculture operations, it is found in the hexavalent form (Cr^{6+}). In natural waters a large proportion can also be bound to suspended solids and sediment (Zweig et al. 1999). Natural background concentrations are usually below 5 ppb (0.005 mg/L) and rarely exceed 20 ppb (Dojlido & Best 1993). In surface waters, the most stable forms of chromium are the oxidation states III and VI. Cr^{3+} is poorly soluble and is absorbed readily onto surfaces, while Cr^{6+} is far more soluble and the most common form in freshwater. For this reason, maximum admissible concentrations for chromium generally are based on toxicity data for the hexavalent ion (Svobodova et al. 1993). Chromium is also of concern for aquaculture due to its ability to bioaccumulate.

The speciation and bio-availability of chromium are discussed in more detail in Section 8.3.7.

The toxicity of the hexavalent ion is greater than that of the trivalent ion (Philips 1993, Zweig et al. 1999). Calcium and magnesium levels, and pH affect the toxicity of chromium compounds to fish; at a high pH and high concentration of calcium, the toxicity of chromium is reduced compared with that in soft, acidic waters.

Svobodova et al. (1993) note that with acute poisoning by chromium compounds, the body surface of the fish is covered with mucus, the respiratory epithelium of the gills is damaged and the fish die with symptoms of suffocation.

Guideline notes

It is assumed that when not specified, authors are referring to the more toxic hexavalent ion (VI). DWAF (1996) set its target water quality range at <0.02 mg/L for freshwater aquaculture. Boyd (1990) suggested a level of <0.1 mg/L for freshwater species, while Schlotfeldt and Alderman (1995) suggested 0.05 mg/L. As bioaccumulation is a problem with chromium, the more conservative level proposed by DWAF (1996) is recommended as the guideline for both freshwater and saltwater species (table 9.4.19). In acid soft waters, the recommended guideline can be reduced to <0.002 mg/L (DWAF 1996).

Table 9.4.19 Summary of the recommended water quality guidelines for chromium

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	<0.02 <0.02	freshwater saltwater	DWAF (1996) Professional judgement
General	<0.1 <0.02 <0.05 <0.21 (III) <0.011 (VI) <0.05 (VI)	freshwater species freshwater aquaculture species general freshwater saltwater	Boyd (1990) DWAF (1996) Schlotfeldt & Alderman (1995) EU 1979, US EPA 1993 EU 1979, US EPA 1993 EU 1979, US EPA 1993
Freshwater fish	<0.05 <0.1	rainbow trout no effect limit for salmonids	Holliman (1993) Klontz (1993)
Edible bivalves	0.045	1/100th of 48 hr EC ₅₀ blue mussel embryos	Seed & Suchanek (1992)

7. Copper

Copper (Cu) is used in antifouling paints, applied to boats and submerged structures. In addition, copper is used as fungicides and algicides. These uses, as well as copper mining activities are the major source of copper contamination in the aquatic environment (Zweig et al. 1999). The most common copper species in natural waters are the free (cupric) ion (Cu^{2+}), and copper hydroxide and carbonate complexes, while it also forms strong complexes with dissolved organic matter. The latter complexes usually control the aqueous copper and/or cupric ion concentration in freshwater systems (Zweig et al. 1999). At higher pH levels, the precipitation of copper carbonate complexes may also control the aqueous copper concentration. 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 sulphides, hydroxides and carbonates (Dojlido & Best 1993). Natural background concentrations of copper in water are typically around 2 $\mu\text{g/L}$ (Dojlido & Best 1993).

Copper is a micronutrient, forming an essential component of many enzymes involved in redox reactions, and is an essential trace element for plants and animals. The DWAF (1996) states that the toxicity of copper depends on the solubility and chemical species of the copper present in the water. Free cupric copper ions (Cu^{2+}) are considered most toxic, and complex forms least toxic to aquatic organisms.

Its toxicity is strongly influenced by the physico-chemical properties of the water. In water with high dissolved organic content, copper can become bound in soluble and insoluble complexes, with reduced toxicities. Zinc exacerbates toxicity of copper. In very alkaline water copper forms hydroxides of low solubility, and in waters with a high bicarbonate/carbonate concentration copper precipitates as poorly soluble or insoluble cupric carbonate. Svobodova et al. (1993) note that compounds that are slow to dissolve or are insoluble are unlikely to be taken up to any extent into the fish body, so their toxicity to fish is low.

The speciation and bio-availability of copper is discussed in further detail in Section 8.3.7.

Although copper is highly toxic to aquatic organisms, its compounds are used in fish culture and fisheries as algicides and in the prevention and therapy of some fish diseases (Svobodova et al. 1993).

Guideline notes

To protect fish, the maximum admissible copper concentration in water is in the range of 0.001 to 0.01 mg/L depending on the species of fish and physico-chemical state of the water (Svobodova et al. 1993). Tebbutt (1977) reported LD₅₀s on fish at between 0.0001–0.0002 mg/L for copper sulphate. Chen et al. (1985) and Boyd (1990) suggested a level of <0.025 mg/L for no known adverse effects on aquaculture fish, while Post (1987) suggested <0.014 mg/L for fish hatcheries. DWAF (1996) and Pillay (1990) suggested <0.005 mg/L for freshwater aquaculture, and as a general guideline, respectively. Therefore, this is recommended as the guideline (table 9.4.20). With increasing hardness and alkalinity, the tolerance level should be increased as suggested by Meade (1989):

- hardness <100 mg/L (as CaCO₃), copper levels should be below 0.006 mg/L
- hardness >100 mg/L (as CaCO₃), copper levels should be less than 0.03 mg/L]

Table 9.4.20 Summary of the recommended water quality guidelines for copper

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	<0.005	freshwater & saltwater (see above notes on hardness)	DWAF (1996), Pillay (1990)
General	<0.005	freshwater & saltwater	Pillay (1990)
	<0.005	freshwater	DWAF (1996)
	0.001–0.01	fish species	Svobodova et al. (1993)
	<0.025	aquaculture fish no effects	Chen et al. (1985), Boyd (1990)
	<0.014	fish hatcheries	Post (1987)
Freshwater fish	<0.006	silver perch	Rowland (1995a)
	<0.03	rainbow trout	Holliman (1993)
	<0.1	rainbow trout	Schlotfeldt & Alderman (1995)
	<0.1	no effect limit for salmonids	Klontz (1993)
Brackish water fish	<0.02	barramundi fingerlings	Nowak & Duda (1996)
Freshwater crustaceans	<0.03	hard water	Swindlehurst pers comm
	<0.006	soft water	Swindlehurst pers comm
Marine crustaceans	0.1	black tiger prawn	Chen (1985)
Edible bivalves	<0.008	recommended for Sydney rock oysters	Nell & Chvojka (1992)
	<0.005	1/10th of 15 d LC ₅₀ s for blue mussel	Seed & Suchanek (1992)
Gastropods	<0.006	1/10th of 96 hr LD ₅₀ abalone	Hahn (1989)

8. Cyanide

Cyanide (CN) is used in a variety of industrial processes, in particular, those involved with metal, petroleum and mineral processing. It is a non-cumulative biodegradable poison (SECL 1983) and can form a large number of complexes with metals, with varying toxicities according to their ability to dissociate into metal and hydrocyanic acid (HCN) which is the most toxic form of cyanide. For example, the toxicity of the iron cyanide complex is low to very low to fish, but the complex cyanides of zinc, cadmium, copper and mercury are highly toxic (Svobodova et al. 1993).

Cyanide also can be present in water as simple compounds (non-dissociated HCN or simple CN⁻ ions). These can be very toxic or extremely toxic to fish species.

Cyanide toxicity is affected by the pH of the water: if pH is low the proportion of nondissociated HCN increases and so does the toxicity. Svobodova et al. (1993) note that

toxicity is also markedly enhanced by an increase in water temperature and a decrease in the concentration of dissolved oxygen in the water.

The mechanism of toxic action of cyanides is based on their inhibition of respiratory enzymes (Svobodova et al. 1993).

According to Klontz (1993), increased temperatures in pond water can enhance the growth of cyanogenic blue-green algae, the decomposition of which can release cyanide. It is particularly a problem in large reservoirs in which plant nutrients can flow (e.g. in agricultural run-off).

Guideline notes

Schlotfeldt and Alderman (1995) suggested a level below 0.1 mg/L for freshwater aquaculture, although the more conservative recommendation of Alabaster and Lloyd (1982) is used as the guideline. Meade (1989) suggested the hydrogen cyanide levels for all aquaculture should be below 0.005 mg/L. Published information suggests that 85% of cyanide is lost from seawater within 16 hours due to volatility of the chemical (Heffer & Longmore 1984), suggesting it may be of little concern to saltwater aquaculture species. However, to be conservative the suggestion of Meade (1989) is used as the recommended guideline for all aquaculture (table 9.4.21).

Table 9.4.21 Summary of the recommended water quality guidelines for cyanide

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	<0.005	freshwater & saltwater	Meade (1989)
General	<0.005	freshwater	Alabaster & Lloyd (1982)
	<0.1	freshwater	Schlotfeldt & Alderman (1995)
	not of concern	saltwater	Heffer & Longmore (1984)
	<0.005	all aquaculture	Meade (1989)
Freshwater fish	0.03–0.5	freshwater species	Svobodova et al. (1993)
	<0.02	no known adverse effects	DWAF (1996)
	<0.005	salmonid hatchery	SECL (1983)
	<0.005	rainbow trout	Forteach pers comm

9. Fluorides

Very little reference was made in the scientific literature examined for this report on the effects of fluorides on aquaculture species. It has been reported that city water supplies can cause problems for aquarium fish due to high levels of fluorides (Datodi, pers. comm.).

Guideline notes

Tebbutt (1977) suggested that the safe level for freshwater fish was 0.2 to 1.0 mg/L. This is recommended as the guideline for freshwater aquaculture (table 9.4.22). Insufficient information is available to set a recommended guideline for saltwater aquaculture. Therefore, the guidelines for ecosystem protection should be used.

Table 9.4.22 Summary of the recommended water quality guidelines for fluoride

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	<0.2	freshwater	based on Tebbutt (1977)
	ND	saltwater	
Freshwater fish	0.2–1.0		Tebbutt (1977)
Edible bivalves	<0.025	blue mussel	Pankhurst et al. (1980)
	<30.0	Sydney rock oyster spat 20% growth reduction	Nell & Livanos (1988)

ND: Not determined — insufficient information

10. Hydrogen sulphide

Sulphide is the -II oxidation state of sulphur and can exist in solution as un-ionised hydrogen sulphide gas (H_2S) or as soluble sulphides (S_2^-). H_2S is produced by bacteria in oxygen depleted (anoxic) conditions. It can be found in source water taken from ground water, and anoxic areas of surface water. It is of great concern to aquaculture as it is very toxic to fish (Zweig et al. 1999). H_2S is also present in industrial effluents, including those from metallurgical and chemical works, pulp and paper plants and tanneries.

Under anaerobic conditions, certain heterotrophic bacteria can use sulphate and other oxidised sulphur compounds in metabolism which results in the release of hydrogen sulphide (Boyd 1989). It can escape (with other gases, e.g. methane and carbon dioxide) from rich organic mud and bubble into the overlying waters. Un-ionised hydrogen sulphide is a highly toxic gas, however, the ionic forms, have no appreciable toxicity. The pH regulates the proportion of total sulphides among its forms (H_2S , HS^- and S_2^-); as pH increases, the proportion of ionised species increases and the toxicity decreases (Svobodova et al. 1993).

H_2S is often found in mangrove muds, which when disturbed (e.g. during the building of fish or prawn ponds) will become oxidised. The consequent drop in pH can lead to the mobilisation of a range of heavy metals include Al and Fe.

Guideline notes

There is a wide variation in literature for the recommended levels. Meade (1989) suggested that for aquaculture, sulphate, hydrogen sulphide and sulphur concentrations should not exceed 50 mg/L, 0.003 mg/L and 1 mg/L, respectively. The recommendation for hydrogen sulphide by Schlotfeldt and Alderman (1995) of <1.0 mg/L for freshwater aquaculture is much higher than that of other authors and is possibly for the ionic forms. According to Boyd (1989), concentrations of 0.01 to 0.05 mg/L of H_2S may be lethal to aquatic organisms, and any detectable concentration of H_2S is considered undesirable. Zweig et al. (1999) recommend that source water found to have even low levels of H_2S should not be used for aquaculture.

The DWAF (1996) suggestion is recommended as the guideline for freshwater whilst a slightly higher one is used for saltwater species (table 9.4.23) based on data for marine species.

Table 9.4.23 Summary of the recommended water quality guidelines for hydrogen sulphide

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	<0.001	freshwater	DWAF (1996)
	<0.002	saltwater	Professional judgement
General	<0.001	freshwater	DWAF (1996)
	<0.003	all aquaculture	Meade (1989)
	<0.01	aquatic organisms	Boyd (1990)
	<1.0	freshwater	Schlotfeldt & Alderman (1995)
Freshwater fish	<0.002	silver perch	Rowland (1995a)
	<0.002	salmonids	SECL (1983)
Marine fish	<0.002	Atlantic salmon	Klontz (1993)
Brackish water fish	<0.3	barramundi	Rimmer (1995)
Freshwater crustaceans	<0.1	temperate water species	
Marine crustaceans	<0.002	black tiger prawn	Lee & Wickins (1992)
	<0.033	black tiger prawn	Chen (1985)
Gastropods	<1.0	higher is toxic to abalone	Fallu (1991)

11. Iron

In natural systems, iron can be present in two oxidation states, either the reduced soluble ferrous ion (Fe^{2+}) or the oxidised insoluble ferric ion (Fe^{3+}). The ratio of these two ions depends on the oxygen concentration in the water, pH and other chemical properties of the water. Iron is a micro-nutrient that has been shown to be occasionally limiting in seawater. It is usually found as $\text{Fe}(\text{OH})_3$.

Soluble ferrous iron can be oxidised to insoluble ferric compounds on the alkaline surfaces of fish gills. At a low water temperature and in the presence of iron, iron-depositing bacteria will multiply rapidly on the gills and further contribute to the oxidation of ferrous iron compounds. This can give the gills a brown colour. Fish can suffocate if these compounds build up and reduce the gill area available for respiration (Svobodova et al. 1993). Ferrous iron oxidation also can affect pond productivity by taking up phosphate and restricting plankton growth.

The soluble ions may be present in bore water (artesian) in high concentrations. Upon aeration, these oxidise (and precipitate) to ferric oxide which can form crystals on the gills of fish and crustaceans. Aeration prior to use may minimise the negative effects on culture species.

Guideline notes

The level suggested by Schlotfeldt and Alderman (1995) of <2.0 mg/L total iron for freshwater aquaculture is higher than the other guidelines (e.g. <0.1 mg/L in DWAF 1996) which are for the ionic (ferrous) state. The limit of <0.01 mg/L as given in Meade (1989) is recommended as the guideline for freshwater and saltwater aquaculture (table 9.4.24). This level was also recommended for saltwater by Huguenin and Colt (1989) and Svobodova et al. (1993). The data presented in table 9.4.24 suggest that the toxicity may be higher for finfish than crustaceans and molluscs, although additional data is required to confirm this hypothesis.

Table 9.4.24 Summary of the recommended water quality guidelines for ferrous iron

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	<0.01	freshwater & saltwater	Meade (1989)
General	<0.01	aquaculture	Meade (1989)
	<0.01	saltwater	Huguenin & Colt (1989), Svobodova et al. (1993)
	<2.0	freshwater (total iron)	Schlotfeldt & Alderman (1995)
Freshwater fish	<0.1	rainbow trout	Holliman (1993)
	<0.5	silver perch	Rowland (1995a)
	<0.01	no known adverse effects	DWAF (1996)
	<0.1	no effect limit for salmonids	Klontz (1993), Svobodova et al. (1993)
	0.01	fish hatchery	Pillay (1990)
Brackish water fish	<0.02	barramundi	Curtis pers comm
Freshwater crustaceans	<0.1	temperate freshwater crayfish	
Marine crustaceans	<1.0	black tiger prawn	Chen (1985), Lee & Wickins (1992)

12. Lead

Major sources of lead (Pb) to aquatic systems include atmospheric deposition of exhaust emissions, improper disposal of batteries, lead ore mine wastes and lead smelters, sewage discharge, stormwater runoff, and agricultural runoff from fields fertilised with sewage sludge (Zweig et al. 1999).

The lead ion (Pb^{2+}) and hydroxide species dominate at pH ~6. At higher pH, lead hydroxide and carbonate species tend to dominate. Lead forms sulfate and carbonate precipitates, while it also complexes with organic and particulate matter (Zweig et al. 1999). Concentrations of dissolved lead are generally low due to either precipitation of carbonate species or adsorption to particulates, and natural background concentrations rarely exceed 20 ppb (0.020 mg/L) (Dojlido & Best 1995). Some evidence exists for the formation of lead organometallic compounds that can bioaccumulate (Schmidt & Huber 1976). Lead largely accumulates in the bottom sediments at concentrations about four orders of magnitude greater than in the water.

The solubility of lead compounds is reduced with increasing alkalinity and pH as well as with increasing calcium and magnesium concentrations (i.e. lead is more toxic in acid soft water).

The speciation and bio-availability of lead is discussed in more detail in Section 8.3.7.

Acute lead toxicity is characterised initially by damage to the gill epithelium, the affected fish die from suffocation (Svobodova et al. 1993).

Guideline notes

Effects vary with hardness of water. Post (1987) suggested a level of <0.01 mg/L in softwater and <4.0 mg/L in hardwater. The DWAF (1996) recommendation was for no known adverse effects in soft water. The levels provided by Eisler (1988b) for changing hardness are used for the recommended guidelines (table 9.4.25 & table 4.4.2, Vol. 1):

- <0.001 mg/L at 0–60 mg/L CaCO_3
- <0.002 mg/L at 60–120 mg/L CaCO_3
- <0.004 mg/L at 120–180 mg/L CaCO_3
- <0.007 mg/L at >180 mg/L CaCO_3

These are significantly lower than the suggestion by Meade (1989) for all aquaculture species as well as the recommendations of some other authors, however it was decided to take the more conservative figure (table 9.4.25).

Table 9.4.25 Summary of the recommended water quality guidelines for lead

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	<0.001–0.007	freshwater & saltwater (see above notes on hardness)	Eisler (1988b)
General	<0.001	freshwater	DWAF (1996)
	<0.02	all aquaculture	Meade (1989)
	<0.01–4.0	depends on hardness	Post (1987)
	<0.001–0.007	depends on hardness	Eisler (1988b)
Freshwater fish	0.004–0.008	salmonids	Svobodova et al. (1993)
	<0.03	silver perch	Rowland (1995a)
	<0.03	rainbow trout	Forteach pers comm, Schlotfeldt & Alderman (1995)
	<0.01	rainbow trout	Holliman (1993)
	<0.1	no effect limit for salmonids	Klontz (1993)
Non edible bivalves	<0.02	1/10th of levels for 50% reduction in juvenile blue mussel shell growth	Seed & Suchanek (1992)

13. Magnesium

Magnesium is a major component in the hardness of water along with calcium (see 9.4.2.1/7). However, little data were found in the literature discussing its effects on aquaculture species.

Guideline notes

Meade (1989) recommended that magnesium not exceed 15 mg/L for all freshwater aquaculture species. No information is available for saltwater species, so no guideline is provided (table 9.4.26).

Table 9.4.26 Summary of the recommended water quality guidelines for magnesium

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	<15 ND	freshwater saltwater	Meade (1989)
General	<15	freshwater only	Meade (1989)
Freshwater fish	<15–20	fish hatchery	Pillay (1990)

ND: Not determined — insufficient information

14. Manganese

Manganese is used in a number of industries, producing alloys, pigments, glass, fertilisers and herbicides. It can be found in several oxidation states, namely -III, -I, 0, I, II, III, IV, V, VI and VII. It is an essential micronutrient for vertebrates but is neurotoxic in excessive amounts. At typical concentrations encountered in surface waters, manganese has aesthetic rather than toxic effects as it produces a slight green discolouration of the water (DWAF 1996). The oxidised form, Mn⁴⁺, is far less soluble than the reduced form, Mn²⁺. If high concentrations of reduced manganese are present in source water, it will oxidise and precipitate causing similar problems as iron (see 9.4.2.2/11; Zweig et al. 1999).

Typically, the median concentration of manganese in freshwater is 8 µg/L (range 0.02 to 130 µg/L) and 2 µg/L in sea water. However, DWAF (1996) notes that manganese concentrations in the mg/L range can be found in anaerobic bottom waters where manganese has been mobilised from the sediments.

Guideline notes

Tolerance to manganese depends on total water chemistry, such as pH. Schlotfeldt and Alderman (1995) suggested a range between 0.1 and 8.0 mg/L, while DWAF (1996) suggested <0.1 mg/L for freshwater aquaculture. Meade (1989) and Zweig et al. (1999) recommended that manganese not exceed 0.01 mg/L for all aquaculture species, and this is the guideline recommended here (table 9.4.27).

Table 9.4.27 Summary of the recommended water quality guidelines for manganese

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	<0.01	freshwater & saltwater	Meade (1989), Zweig et al. (1999)
General	<0.01 0.1–8.0 <0.1	freshwater & saltwater freshwater freshwater	Meade (1989), Zweig et al. (1999) Schlotfeldt & Alderman (1995) DWAF (1996)
Freshwater fish	<0.01 <0.02 <5.0	silver perch rainbow trout fish hatchery	Rowland (1995a) Holliman (1993) Pillay (1990)

15. Mercury

Mercury (Hg) naturally occurs in the environment due to the volcanic degassing of the Earth's crust and weathering of mercury rich geology (Zweig et al. 1999). While naturally high background concentrations of mercury may occur in areas rich in mercury ores, the most significant causes of aquatic contamination occur through industrial processes, agriculture and the combustion of fossil fuels. Common sources include caustic soda, pulp and paper production and paint manufacturing (Zweig et al. 1999). In most cases, background levels in unpolluted waters will contain trace amounts of mercury which do not exceed 0.0001 mg/L (Svobodova et al. 1993, Zweig et al. 1999).

The bioavailability of mercury is discussed in more detail in Section 8.3.7.

As mercury readily accumulates in sediments, surface water concentrations are not a true representation of the actual total amount of mercury present. Elementary mercury and its organic and inorganic compounds can undergo methylation (a process induced by the activity of microorganisms) in the sediments. According to Svobodova et al. (1993), the toxic end-product of this methylation — methyl mercury — enters the food chains and bioconcentrates in increasing amounts in aquatic organisms up the food chain. They give a recommended safe level of 0.0003 mg/L with organic mercury compounds for fish in general.

Mercury can be taken up by fish from food via the alimentary tract; the other routes are through the gills and skin. Through the bioaccumulation process, carnivorous fish contain the highest amounts of mercury because they form the final link in the aquatic food chain (Svobodova et al. 1993). Aquatic invertebrates can also accumulate mercury to high concentrations (Zweig et al. 1999).

Mercury compounds may damage vital tissues and organs, including gills, liver, kidney, brain and skin in fish and also may have a harmful effect on reproduction.

Guideline notes

Recommendations vary significantly between authors. A low level of 0.00005 mg/L for freshwater is suggested by Schlotfeldt and Alderman (1995), while higher limits of <0.001 mg/L (Boyd 1990) and 0.02 mg/L (Meade 1989) have been suggested for all aquaculture species. For both freshwater and saltwater species, the median level of <0.001 mg/L is selected as the recommended guideline (table 9.4.28).

Table 9.4.28 Summary of the recommended water quality guidelines for mercury

Group	Guideline mg/L	Comments	Reference
Recommended guideline	<0.001	freshwater & saltwater	Professional judgement
General	<0.0005	freshwater	Schlotfeldt & Alderman (1995)
	<0.001	all aquaculture species	Boyd (1990)
	<0.02	all aquaculture species	Meade (1989)
Freshwater fish	0.001	salmonids	Svobodova et al. (1993)
	<0.002	silver perch	Rowland (1995a)
	<0.01	rainbow trout	Holliman (1993)
	<0.001	no known adverse effects	DWAF (1996)
Marine crustaceans	<0.0025	black tiger prawn	Chen (1985)
Edible bivalves	<0.00004	1/10th of level for 50% shell growth reduction in juvenile blue mussels	Seed & Suchanek (1992)

16. Methane

The reduction of organic matter under anaerobic conditions can cause the frequent release of bubbles which rise from sediments through the water column. This gas is mostly methane, although several other gases also can be formed including hydrogen sulphide, nitrogen, ammonia and carbon dioxide. Odourless and flammable, methane might be found in water taken from the bottom of lakes or reservoirs during summer (Zweig et al. 1999).

Guideline notes

McKee and Wolf (1963) and Boyd (1990) reported that a methane level of less than 65 mg/L had no effects on freshwater and marine fish so this level is recommended for freshwater and saltwater culture (table 9.4.29), although there is a paucity of information on the effects on different species.

Table 9.4.29 Summary of the recommended water quality guidelines for methane

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	<65	freshwater & saltwater	McKee & Wolf (1963), Boyd (1990)
Freshwater fish	<65	no effects	McKee & Wolf (1963), Boyd (1990)
Marine fish	<65	no effects	McKee & Wolf (1963), Boyd (1990)

17. Nickel

Nickel (Ni) contaminates surface waters through effluents from metal plating industries and ore processing facilities, while it is also emitted by the combustion of petroleum products and used to manufacture batteries (Zweig et al. 1999).

The dominant form of nickel in aquatic systems is the free ion, Ni²⁺. It forms strong complexes with humic acids and adsorbs well to particulate matter (Zweig et al. 1999). However, in natural waters it is predominantly in dissolved form (Dojlido & Best 1993). Typical background concentrations of nickel in surface waters range from 1–3 ppb (0.001–0.003 mg/L), with concentrations up to 50 ppb (0.05 mg/L) in industrialised areas (Dojlido & Best 1993).

Nickel compounds are of medium toxicity to fish according to Svobodova et al. (1993). Their toxicity is influenced markedly by the physico-chemical properties of the water, especially hardness (the toxicity is increased in soft waters).

The speciation and bioavailability of nickel is discussed in more detail in Section 8.3.7.

After toxic exposure to nickel compounds, the gill chambers of fish are filled with mucus and the lamellae are dark red in colour (Svobodova et al. 1993).

Guideline notes

The toxicity of nickel depends on hardness with the highest toxicity in soft waters. As the little information available varies markedly, the recommended guideline is that suggested by Meade (1989), of <0.1 mg/L for all aquaculture species (table 9.4.30).

18. Nitrate

Nitrate is the least toxic of the major inorganic nitrogen compounds (Zweig et al. 1999). As it is the end-product of the nitrification process, the concentration of nitrate is generally higher than both ammonia and nitrite (Zweig et al. 1999). The main sources of nitrate pollution in surface waters are the use of nitrogenous fertilisers and manures on arable land leading to diffuse inputs, and the discharge of sewage effluents from treatment works (Svobodova et al. 1993).

Table 9.4.30 Summary of the recommended water quality guidelines for nickel

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	<0.1	freshwater & saltwater	Meade (1989)
General	<0.1	all aquaculture species	Meade (1989)
Freshwater fish	0.02	trout	Schlotfeldt & Alderman (1995)
	0.134	LOEC at 33 mg/L CaCO ₃ , pH 7	Atchinson et al. (1987)
	0.024	LOEC at 28 mg/L CaCO ₃ , pH 7.3	Atchinson et al. (1987)
	8	salmonid 96 h LC ₅₀ — softwater	EIFAC (1984)
	50	salmonid 96 h LC ₅₀ — hardwater	EIFAC (1984)
Edible bivalves	<0.02	1/10th of level for 50% reduction in shell growth in juvenile blue mussels	Seed & Suchanek (1992)

Nitrate is not recognised generally as being toxic to aquatic animals (SECL 1983). However, high nitrate concentrations (i.e. much higher than toxic concentrations of ammonia or nitrites) can impair osmoregulation and oxygen transport (Lawson 1995). As nitrate is the major plant-limiting nutrient in seawater (most phytoplankton grow well at a nitrogen:phosphorus ratio of 10:1), so high nitrate levels can result in eutrophication and excessive nuisance algal and plant growth (Zweig et al. 1999). This can have negative effects on culture species and can result in deaths due to changes in oxygen/carbon dioxide levels. CCME (1993) recommended that nitrate levels that stimulate prolific weed growth should be avoided.

Schlotfeldt and Alderman (1995) suggested that increasing nitrate levels signals organic pollution, and measures should be taken to reduce this input. However, high nitrate levels can be a sign that nitrification (conversion of ammonia to nitrate by certain bacteria) is occurring which is helping to reduce the levels of toxic ammonia (Burford, pers. comm. 2000).

Nitrate is known to accumulate to high levels in recirculation systems as an end-product of nitrification. Through the process of denitrification it can be converted to N₂ gas, so high nitrate levels can indicate that denitrification is not occurring.

High nitrate levels (e.g. >50 mg/L) could be a potential problem under conditions of low dissolved oxygen and high pH, both of which could be further lowered by an algal bloom stimulated by the excess nitrate.

Guideline notes

Coche (1981) and Pillay (1990) recommended a level of <100 mg/L for farmed fish, molluscs and crustaceans, and this level is used as the guideline for saltwater species (table 9.4.31). However, it should be noted that nitrate levels around 100 mg/L could be a danger under conditions of low oxygen and high pH since it could be reduced to ammonia (9.4.2.2/2).

Meade (1989) was much more conservative than all the species-specific levels, and suggested a level of 3.0 mg/L for aquaculture. However, a higher level of <50 mg/L is recommended for freshwater (table 9.4.31), as suggested by Schlotfeldt and Alderman (1995).

See also discussion under Ammonia (9.4.2.2/2), Nitrite (9.4.2.2/19) and Phosphates (9.4.2.2/20).

Table 9.4.31 Summary of the recommended water quality guidelines for nitrate

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	<50	freshwater	Schlotfeldt & Alderman (1995)
	<100	saltwater	Coche (1981), Pillay (1992)
General	<50	freshwater	Schlotfeldt & Alderman (1995)
	<100	saltwater	Coche (1981), Pillay (1992)
	<3.0	all aquaculture species	Meade (1989)
Freshwater fish	<100	silver perch	Rowland (1995a)
	<20	rainbow trout	Svobodova et al. (1993)
	<300	no known adverse effects on fish	DWAF (1996)
	<400	tolerated	Muir (1982)
Brackish water fish	<100	barramundi	Curtis pers comm
Freshwater crustaceans	<100	freshwater crayfish	Wingfield pers comm
Marine crustaceans	100–200	black tiger prawns	Lee & Wickins (1992)

19. Nitrite

Nitrite is an intermediate product in the conversion of ammonia to nitrate, a process known as nitrification. Nitrite is usually rapidly converted to nitrate, thus, high concentrations are uncommon in most aquatic systems (Zweig et al. 1999). Nitrite is rarely a source water problem, and is of more concern during the operation of recirculating systems where the water is continually reused (Lawson 1995). However, in prawn ponds, nitrite levels may increase to quite high levels at times. This appears to be a problem, particularly in tropical regions, although the cause is unclear (Burford pers comm 2000).

Nitrite toxicity results in a reduction of the activity of haemoglobin; this can be toxic to finfish or crustaceans. The brown blood disorder in fish is where haemoglobin is converted into meta-haemoglobin.

According to Schwedler et al. (1985) the following factors affect nitrite toxicity: chloride concentration in the water, pH, animal size, previous exposure, nutritional status, infection and dissolved oxygen concentration. SECL (1983) suggest that the presence of calcium, size of fish and pH also affect nitrite toxicity.

Nitrites as a rule are found together with nitrates and ammonia nitrogen in surface waters, but their concentrations are usually low because of their instability (Svobodova et al. 1993, Zweig et al. 1999). They are readily oxidised to nitrate or reduced to ammonia, both chemically and biochemically by bacteria. If levels are increasing, it is a sign of organic pollution (Schlotfeldt & Alderman 1995).

The amount of nitrite tolerated by fish is related to the chloride content of the surrounding water (Tomasso et al. 1980). Brackish water has a higher concentration of calcium and chloride which tend to reduce nitrite toxicity, although high ammonia concentrations can increase the toxicity. Svobodova et al. (1993) claimed it was necessary to measure the ratio of chloride to nitrite when estimating the safe nitrite concentration for particular locations.

Most freshwater fish actively transport nitrite from the environment using the chloride uptake mechanism located on the chloride cells of the gills (Tomasso 1993).

Guideline notes

Coche (1981) and Meade (1989) both suggested a level of <0.1 mg/L for farmed fish, molluscs and crustaceans and this level is recommended as the guideline for both saltwater and freshwater species (table 9.4.32). However, a higher level of <0.2 mg/L for freshwater is

suggested by Schlotfeldt and Alderman (1995). With increasing temperature the tolerance levels should be decreased. Tolerance levels are lower in soft waters (see table 9.4.32).

See also discussion under Ammonia (9.4.2.2/2), Nitrate (9.4.2.2/18) and Phosphates (9.4.2.2/20).

Table 9.4.32 Summary of the recommended water quality guidelines for nitrite

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	<0.1	freshwater & saltwater	Coche (1981), Meade (1989)
General	<0.1	freshwater & saltwater	Coche (1981), Meade (1989)
	<0.2	freshwater & saltwater	Schlotfeldt & Alderman (1995)
Freshwater fish	<0.1	rainbow trout soft water	Forteath pers comm
	<0.2	rainbow trout hard water	Forteath pers comm
	<4.0	silver perch	Francis pers comm
	<0.05	no known adverse effects	DWAF (1996)
	0.06–0.25	warmwater species	DWAF (1996)
	<0.01	salmonid - soft water	Pillay (1990)
Marine fish	<0.1	salmonid - hard water	Pillay (1990)
	<0.3	flounder	Hutchinson et al. (1992)
Brackish water fish	<0.1	barramundi	Curtis pers comm
Freshwater crustaceans	<0.5	all species	Lee & Wickins (1992)
Marine crustaceans	<0.2	black tiger prawn	Lee & Wickins (1992)
	<1.0	black tiger prawn	Chien (1992), Chen (1985)
	<4.5	black tiger prawn and post larvae	Boyd (1990)

20. Phosphates

Phosphate is a generic term for the oxy-anions of phosphorus, namely ortho-phosphate (PO_4^{3-}), hydrogen phosphate (HPO_4^{2-}) and dihydrogen phosphate (H_2PO_4^-). These three ions exist in equilibrium with each other, the position of the equilibria is governed by pH.

Phosphate is not generally recognised as toxic to aquatic organisms. However, it is an important plant nutrient which can assist in stimulating the growth of nuisance organisms, particularly algae in fresh and brackish waters. SECL (1983) recommend that levels in salmonid hatcheries should be kept below 0.025 mg/L.

In Australia, algal blooms are consistently recorded from freshwater when total phosphate levels are over 0.1 mg/L. Research in NSW has shown that local marine algae are nitrogen limited, so it would seem unlikely that phosphate levels would influence bloom culture (Semple pers comm 2000).

High levels of phosphates may result from the use of superphosphate and other fertilisers for agricultural purposes in the catchment. High levels may be present in ponds or tanks through the addition of inorganic fertilisers to assist in promoting microalgal growth for food for zooplankton which, in turn, acts as a feed source for larval fish, molluscs and crustaceans.

Guideline notes

Schlotfeldt and Alderman (1995) suggested a range of 0.6 to 1.0 mg/L for freshwater species. The lower level (<0.1 mg/L) suggested by DWAF (1996) for freshwater farm species is recommended as the guideline as it more closely matches the species specific data (table 9.4.33). For saltwater species the recommended guideline is <0.05 mg/L as this is the most sensitive level for marine fish.

Table 9.4.33 Summary of the recommended water quality guidelines for phosphates

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	<0.1 <0.05	freshwater saltwater	DWAF (1996) Professional judgement
General	<0.1 0.6–1.0	freshwater freshwater species	DWAF (1996) Schlotfeldt & Alderman (1995)
Freshwater fish	<0.1 <0.2	in soft water hard water	Forteach pers comm
Marine fish	<0.05		Swindlehurst pers comm
Brackish water fish	<0.1	barramundi	Curtis pers comm
Freshwater crustaceans	<0.1–0.2		Wingfield pers comm
Marine crustaceans	<0.5 <0.1–0.2		Swindlehurst pers comm Burford pers comm (2000)

See also discussion under Ammonia (9.4.2.2/2), Nitrate (9.4.2.2/18) and Nitrite (9.4.2.2/19).

21. Selenium

Selenium (Se) is an essential element that can be very toxic at low concentrations. The principle sources of selenium in the environment are the burning of fossil fuels and cement production (Dojlido & Best 1993). It exists in a variety of oxidation states, and the most common forms in the environment are selenites and selenates. They possess similar behaviour as sulfites and sulfates (Zweig et al. 1999). The breakdown of organic matter containing selenium results in the formation of organoselenium compounds (Zweig et al. 1999). Natural background concentrations of selenium are typically 0.1 ppb (0.0001 mg/L) (Dojlido & Best 1993). Selenium is of little toxicological concern for marine organisms, and it has been suggested that it may even aid in detoxifying accumulated mercury (Philips 1993).

The speciation and bioavailability of selenium is discussed in more detail in Section 8.3.7.

Guideline notes

Very little data was found for this contaminant. Whilst the USEPA (1993) recommended more conservative values, the recommended guideline is that as suggested by Meade (1989) for all aquaculture species, below 0.01 mg/L (table 9.4.34).

Table 9.4.34 Summary of the recommended water quality guidelines for selenium

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	<0.01	freshwater & saltwater	Meade (1989)
General	<0.01 0.005 0.071	all aquaculture species freshwater saltwater	Meade (1989) US EPA (1993) US EPA (1993)

22. Silver

The major sources of silver (Ag) include ore processing, photography, dentistry and electronics. It is associated with industrialised areas and wherever human beings are located, and is actually a reliable tracer for sewage (Zweig et al. 1999).

The common forms of aqueous silver under aerobic conditions are the free ion (Ag⁺) in freshwater and silver chloride complexes in saltwater (Stumm & Morgan 1996). It can also precipitate as silver sulfide, silver oxide, silver chloride and silver nitrate (Dojlido & Best 1993).

Silver is highly toxic to aquatic life, however, the toxicity is dependent upon which salt is present (Zweig et al. 1999). Silver nitrate exhibits the greatest toxicity, followed by silver chloride and iodide, sulfide and thiosulfate (Zweig et al. 1999). Mortality and altered hatching of rainbow trout has been reported at silver concentrations as low as 0.0005 mg/L (Mance 1987). Molluscs (e.g. oysters) are known to accumulate silver rapidly but depurate slowly, and as such, should not be cultured in areas where elevated silver concentrations exist (Zweig et al. 1999).

Guideline notes

Very little data was found for this contaminant. Whilst Maryland DoE (1993) recommended different guidelines for freshwater and saltwater species, both of which were more conservative than that suggested by Meade (1989) for all aquaculture species, i.e. <0.003 mg/L, and this is used as the recommended guideline (table 9.4.35).

Table 9.4.35 Summary of the recommended water quality guidelines for silver

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	<0.003	freshwater & saltwater	Meade (1989)
General	<0.003	freshwater & saltwater	Meade (1989)
	0.00012	freshwater	Maryland DoE (1993)
	0.0023	saltwater	Maryland DoE (1993)

23. Sulphide — see Hydrogen sulphide (9.4.2.2/10)

24. Total ammonia nitrogen (TAN) — see Ammonia (9.4.2.2/2)

25. Tin and tributyltin

The major sources of tin (Sn) include processing ore and manufacturing of paint and rubber products, while the major source of organotin is the use of tributyltin (TBT) as an antifouling agent for boats and submerged structures (Zweig et al. 1999). It can also derive from plastics industries where it is used as a catalyst, fungicide and disinfectant (Dojlido & Best 1993), as well as tin-based molluscicides (Acosta & Pullin 1991).

Tin hydroxide complexes predominate in natural waters under aerobic conditions (Mance et al. 1988). In natural waters, TBT remains in a slowly degrading form, retaining some of its toxic properties, which accumulates in sediments (Lloyd 1992). Typical natural background concentrations of tin rarely exceed 2 ppb (0.002 mg/L) (Durum & Haffty 1961), while levels of organotins should be negligible unless contamination exists. TBT contamination occurs largely in the marine environment, although will occur anywhere there exists significant boating activity (e.g. marinas; Lloyd 1992).

Tin is moderately toxic to aquatic organisms (Philips 1993), however, organotin compounds are very toxic and are of major concern to aquaculture (Zweig et al. 1999) As a result of their high toxicity and ability to bioaccumulate (Dojlido & Best 1993), organotins have been banned in most states of Australia for use as an antifoulants on vessels smaller than 20–25 m in length.

Guideline notes

Toxic effects of tin have been observed at a concentration of 2 mg/L for fish (Liebman 1958, as cited by Zweig et al. 1999).

For the highly toxic organotins, sediments containing TBT at a concentration of 1 ppb (0.001 mg/kg) were reportedly toxic to clams (Furness & Rainbow 1990).

An environmental quality standard for fish for organotins of 0.00002 mg/L (0.02 ppb) was recommended by Zabel et al. (1988, as cited by Zweig et al. 1999). Standards for TBT in source water have been proposed by Maryland DoE (1993), being <0.000026 mg/L (0.026 ppb) for freshwater and <0.00001 mg/L (0.01 ppb) for saltwater and these are used as the recommended guidelines (table 9.4.36).

Table 9.4.36 Summary of the recommended water quality guidelines for organotins/tributyltin

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	<0.000026 <0.00001	TBT in freshwater TBT in saltwater	Maryland DoE (1993) Maryland DoE (1993)
General	<0.000026 <0.00001	freshwater saltwater	Maryland DoE (1993) Maryland DoE (1993)
Fish	<0.00002	organotins	Zabel et al. (1988, as cited by Zweig et al. 1999)
Edible bivalves	<0.000005 <0.0002 0.00002	Sydney rock oyster Pacific oyster (as TBT acetate) 1/10th of level for 50% reduction shell growth blue mussel juveniles	Nell & Chvojka (1992) Alzieu (1986) Seed & Suchanek (1992)

26. Vanadium

The speciation and bioavailability of vanadium is discussed in Section 8.3.7.

Guideline notes

No data for the species groups is available, so Meade (1989) suggested level of below 0.1 mg/L for aquaculture is used as the recommended guideline (table 9.4.37).

Table 9.4.37 Summary of the recommended water quality guidelines for vanadium

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	<0.1	freshwater & saltwater	Meade (1989)

27. Zinc

Zinc (Zn) enters surface waters primarily as a result of discharges from metal treatment plants, chemical plants and foundries (Dojlido & Best 1993), while mining can also be a major source (Zweig et al. 1999).

In low alkalinity waters, the predominant forms of zinc are the free ion (Zn^{2+}) and hydroxide complexes, while carbonate and sulfate complexes dominate in high alkalinity waters (Zweig et al. 1999). At high pH Zinc can precipitate as zinc hydroxide and coprecipitate with calcium carbonate (Dojlido & Best 1993). Zinc also forms complexes with organic and particulate matter. Natural background concentrations of zinc are generally low, ranging from 5 to 15 ppb (0.005 to 0.015 mg/L)(Moore & Ramamoorthy 1984).

The speciation and bioavailability of zinc is discussed in more detail in Section 8.3.7.

Zinc toxicity is synergistic with copper, and zinc is more toxic in soft water (Lloyd 1992). Rainbow trout are specially sensitive to zinc toxicity, resistance increasing with age. Svobodova et al. (1993) considered that avoiding the use of galvanised pipes for the supply of water and avoiding the use of galvanised containers and equipment, especially in soft and acid waters, is the best remedy to avoid frequent occurrences of zinc toxicity in rainbow trout culture.

The clinical symptoms of zinc poisoning in fish are similar to those found for copper (i.e. gill damage, reduced growth and kidney damage).

Guideline notes

Post (1987) levels at less than 0.01 mg/L for softwater and <0.15 mg/L for hard water. The USEPA (1993) suggested for freshwater aquaculture a level of <0.11 mg/L, and <0.086 mg/L for saltwater aquaculture. Meade (1989), on the other hand, suggested a conservative level below 0.005 mg/L for aquaculture species and this is used as the recommended guideline (table 9.4.38).

9.4.2.3 Organic toxicants

A wide range of agricultural, industrial and domestic activities can result in organic compounds affecting aquaculture species. Organic compounds include antibiotics, oils (petroleum hydrocarbons), pesticides and polychlorinated biphenyls (PCBs).

Table 9.4.38 Summary of the recommended water quality guidelines for zinc

Group	Guideline mg/L	Comments	Reference
Recommended guideline	<0.005	freshwater & saltwater	Meade (1989)
General	<0.11	freshwater	US EPA (1993)
	<0.086	saltwater	US EPA (1993)
	<0.01	softwater	Post (1987)
	<0.15	hardwater	Post (1987)
	<0.005	aquaculture species	Meade (1989)
Freshwater fish	<0.01	rainbow trout	Svobodova et al. (1993)
	<0.1	salmonids	Klontz (1993)
	<0.01	rainbow trout	Holliman (1993)
	<0.05	silver perch	Rowland (1995a)
Marine crustaceans	<0.25	black tiger prawn	Chen (1985)
Edible bivalves	<0.006	1/10th of level for 50% reduction in shell growth blue mussel juveniles	Seed & Suchanek (1992)

1. Antibiotics and antimicrobial agents

Industries requiring the control of microbes (e.g. agriculture) may contaminate source water with unwanted antibiotics and antimicrobial agents (Zweig et al. 1999). For example, iodine is regularly used in veterinary drugs, agricultural chemicals and sanitising solutions (WHO 1989). The presence of such chemicals in source water may have adverse effects on the natural microbial communities that are essential for the health of culture species. In addition, disturbance of microbial communities can also provide ideal conditions for opportunistic pathogens (Zweig et al. 1999).

The effects of antibiotics and antimicrobials depends largely on their bioavailability. Molecules that are bound to sediments and other substrates are generally not bioavailable. Sensitive methods exist for the detection of very low levels of these agents, however, these levels may be representative of many antibiotic and antimicrobial chemical complexes that are not biologically active (Zweig et al. 1999).

Guideline notes

No data are available to provide guidelines for antibiotics and antimicrobials. However, it is recommended that due care should be taken when using such chemicals in aquaculture operations.

2. Detergents and surfactants

Surfactants are compounds which, by lowering the surface tension of water, can facilitate the formation of emulsions with otherwise immiscible liquids such as oils and fat. They are used widely in domestic and industrial operations, eg soaps, water softeners, perfumes, optical brighteners (Svobodova et al. 1993). Aquaculture species can be exposed to surfactants and the detergents that contain them through external and on-farm activities.

There are a large number of synthetic surfactants in production, and they span a wide range of chemical toxic actions for aquatic organisms. They all damage the lipid components of cell membranes and may impair gill respiratory epithelium. Surfactants are usually categorised into three groups, anionic, non-ionic and cationic. Anionic surfactants comprise such common groups as *linear alkylbenzene sulfonates* (LAS) and *alkyl ethoxylated sulfates* (AES). Non-ionic surfactants include *alcohol ethoxylates* (AE) and *alkylphenol ethoxylates* (APE). Cationic surfactants comprise quaternary ammonium compounds. Volume 2 (Section 8.3.7.21) provides further details on surfactants, including brief information on analytical methods.

The toxicity in fish is influenced by a number of biotic and, especially, abiotic factors including pH. According to Svobodova et al. (1993) older fish are more tolerant; however, the acute toxicity varies considerably between species.

Guideline notes

Due to the paucity of information it is difficult to set a suggested level for surfactants for the protection of aquaculture species. Therefore, it is recommended that the trigger values derived for the protection of aquatic ecosystems (Vol 2, Section 8.3.7.21) are used for freshwater and saltwater farm species (table 9.4.39).

See also Section 9.4.3 for discussion on human health aspects.

Table 9.4.39 Summary of the recommended water quality guidelines for detergents and surfactants

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	0.28	LAS: freshwater	Volume 2, Section 8.3.7.21
	0.0001	saltwater*	
	0.65	AES: freshwater	
	0.65	saltwater*	
	0.14	AE: freshwater	
	0.14	saltwater*	

* Low reliability trigger value, for use only as an indicative interim working level.

3. Oils and greases (including petrochemicals)

As components of liquid and gaseous fuels, petroleum hydrocarbons are among the most widely processed and distributed chemical products in the world (Zweig et al. 1999). Primary sources in surface waters include runoff from roads and discharges from industries using oil (Dojlido & Best 1993). At sea, spills from commercial or recreational shipping can cause problems for aquaculture. Mortalities and loss of production can occur, although

the major concern to aquaculture is the tainting of culture animals with off-flavours (Zweig et al. 1999).

It is generally agreed that the lighter oil fractions (kerosene, petrol, benzene, toluene and xylene) are much more toxic to fish than the heavy fractions (heavy paraffins and tars). Fish species can differ significantly in their sensitivity to these compounds — the fry of predatory fish (e.g. trout) show the greatest sensitivity to refined products. The naphthenic acids, which are acute nerve poisons, can kill fish at concentrations as low as 0.03 to 0.1 mg/L (Svobodova et al. 1993).

In general, oils of animal or vegetable origin are chemically non-toxic to aquatic life, although they can taint the flesh of food species, coat gills reducing oxygen uptake, increase BOD levels and increase maintenance of water treatment equipment in hatcheries (SECL 1983).

Guideline notes

Given the wide range of toxicities associated with the wide variety of petroleum derived oils, greases and other chemicals which can pollute aquaculture waters, SECL (1983) consider that it is difficult to develop meaningful criteria. They recommend that surface waters should be kept free of these contaminants. With regard to freshwater aquaculture species, Schlotfeldt and Alderman (1995) provided a level of <0.3 mg/L for petroleum, <0.004 mg/L for gasoil and <1.0 mg/L for benzene. A level below 0.3 mg/L is recommended as the guideline for petroleum products in freshwater aquaculture (table 9.4.40). Insufficient information was available to set a guideline for saltwater aquaculture.

See also Section 9.4.3 for a discussion on human health aspects.

4. Pesticides

Pesticide is the general term given to any chemical used to control unwanted nonpathogenic organisms (Zweig et al. 1999). Examples of pesticides include insecticides, acaricides, herbicides, algicides, and fungicides. They are used in a range industries, but predominantly in agriculture. Johnson and Finley (1980) summarised toxicity of 400 toxic chemicals to fish and aquatic invertebrates (see also Svobodova et al. 1993 and Zweig et al. 1999).

Table 9.4.40 Summary of the recommended water quality guidelines for oils and greases (including petrochemicals)

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	<0.3 ND	freshwater (petroleum) saltwater	Schlotfeldt & Alderman (1995)
General	<0.3 <0.004 <1.0	freshwater for petroleum freshwater for gasoil freshwater for benzene	Schlotfeldt & Alderman (1995) Schlotfeldt & Alderman (1995) Schlotfeldt & Alderman (1995)
Freshwater fish	0.05 to 20	1/100th 48 hr LC ₅₀	Svobodova et al. (1993)
Edible bivalves	<0.1	crude oil 1/10th 4 d LC ₅₀ (blue mussels)	Seed & Suchanek (1992)

ND Not determined — insufficient information

Many pesticides are highly toxic and persistent, and pose significant risks to fish and shellfish health. In addition, due to the bioaccumulative potential of many pesticides, there are risks to product quality and public health (Zweig et al. 1999). Many pesticides used today are less persistent, degrading to non-toxic forms within a few days; however, they are potentially harmful until they are degraded. Thus, the use of pesticides in aquatic farming areas should be discouraged.

Pesticides can be separated into seven categories: inorganic pesticides, organophosphorus pesticides, carbamates, urea pesticides, pyridinium pesticides, phenoxyacetic acid derivatives, and triazine derivatives (Dojlido & Best 1993). The chlorinated pesticides are usually of most concern due to their persistence and ability to bioaccumulate in fish and shellfish (Zweig et al. 1999).

Some herbicides and most pesticides have a broad action and are, therefore, also toxic to many non-target aquatic animals and micro-organisms. They can enter aquatic systems through direct spraying (to control the growth of aquatic weeds or insect pests) or indirectly through leaching and run-off from agricultural soils (DWAF 1996).

Guideline notes

A wide range of chemicals are used by primary industries in Australia and New Zealand to control animal and plant pests. There is very little information available on the effects of these chemicals on cultured species, and it was not possible to determine which chemicals pose the greatest threat to aquaculture. Available data on safe levels for aquaculture species are provided in table 9.4.41. Recommended guidelines are provided in bold, however, it should be noted that the effects vary considerably between species. It is also worthwhile consulting the guidelines for aquatic ecosystem protection (Chapter 3 of Volume 1, Volume 2).

See also Section 9.4.3 for discussion on human health aspects.

5. Phenols

Phenolic compounds include a wide variety of organic chemicals that arise from distillation of coal, wood, oil refineries, chemical plants, production of synthetic fibres, human and other organic sources, and degradation of pesticides. They also arise from naturally occurring sources and substances (SECL 1983).

Phenol is an organic compound consisting of a hydroxyl group attached to a benzene ring. Phenols are anaesthetics which affect the central nervous system of fish.

DWAF (1996) noted the following factors influence the lethal concentrations of phenols:

- with increasing temperature, the resistance of fish to phenols is increased;
- low dissolved oxygen concentrations decrease the lethal concentration of phenols;
- with increasing total hardness, phenol LC₅₀ values increase substantially; and
- sensitivity to phenols increases with an increase in salinity.

These can be problems due to direct toxicity, increases in BOD and the tainting of flesh adversely affecting sales for human consumption, especially chlorophenols (which are formed from the chlorination of phenols). According to Svobodova et al. (1993), the maximum concentrations admissible for fish culture are 0.001 mg/L for chlorophenols, 0.003 mg/L for cresol, 0.004 mg/L for resorcine and 0.001 mg/L for hydroquinone.

Guideline notes

According to Svobodova et al. (1993), the maximum concentrations admissible for fish culture are 0.001 mg/L for chlorophenols, 0.003 mg/L for cresol, 0.004 mg/L for resorcine and 0.001 mg/L for hydroquinone. The more conservative suggestion by Schlotfeldt and Alderman (1995) for freshwater species is taken as the recommended guideline for phenols as a group (table 9.4.42).

Table 9.4.41 Water quality guidelines for 'safe levels' of pesticides, herbicides, etc

Chemical	Safe level (µg /L)	Species/Group	Source
2,4-D	4.0	fish	Pillay (1990)
	<0.004	fish culture	Langdon (1988)
	0.5	rainbow trout	Forteach pers comm
2,4-dichlorophenol	<4.0	freshwater aquaculture	DWAF (1996)
Acephate	<4.7	rainbow trout	Forteach pers comm, Davies et al. (1994)
Aldrin	0.003	pond aquaculture species	Lannan et al. (1986)
	<0.01	freshwater aquaculture	DWAF (1996), Pillay (1990), Langdon (1988)
Amitrole	300.0	fish/salmon hatchery	Pillay (1990), SECL (1983)
Atrazine	<0.34	rainbow trout	Davies et al. (1994)
Azinphos-methyl	<0.01	freshwater aquaculture	DWAF (1996)
Azodrin	<0.01	black tiger prawn	Chen (1985)
BP1100	<0.2	black tiger prawn	Chen (1985)
Butchor	<1.0	black tiger prawn	Chen (1985)
Carbaryl	0.02	fish culture	Pillay (1990), Langdon (1988)
Carbamate *	<0.1	freshwater fish	Svobodova et al. (1993)
Carboxylic acid derivatives	<1.0–10.0	1/100th of 48 hr LC₅₀	Svobodova et al. (1993)
Chlordane	0.01	freshwater aquaculture	Lannan et al. (1986)
	0.004	marine aquaculture	Lannan et al. (1986)
	0.010	fish culture	Boyd (1990)
	0.004	fish	Pillay (1990), Langdon (1988)
	<0.025	freshwater aquaculture	DWAF (1996)
	0.01	salmon hatchery	SECL (1983)
Chlordecone	<0.001	fish	Langdon (1988)
Chlorpyrifos	<0.001	freshwater aquaculture	DWAF (1996)
Chlorothalonil	<0.0082	rainbow trout	Forteach pers comm
Cyanazine	0.0035	rainbow trout	Davies et al. (1994)
Cypermethrin	0.00147	rainbow trout	Davies et al. (1994)
DDT	0.001	pond aquaculture species	Lannan et al. (1986)
	0.001	fish	Boyd (1990)
	0.003	fish	Pillay (1990), Langdon (1988)
	0.0001	freshwater aquaculture	Schlotfeldt & Alderman (1995)
	<0.0015	freshwater aquaculture	DWAF (1996)
	0.001	salmonid hatchery	SECL (1983)
	0.001	freshwater life	CCME (1993)
	0.001	rainbow trout	Forteach pers comm
Diazine †	<1.0–10.0	freshwater fish	Svobodova et al. (1993)
Demton	0.01	pond aquaculture species	Lannan et al. (1986)
	0.1	salmonid hatchery	SECL (1983)
Diazinon	0.002	fish culture	Pillay (1990), Langdon (1988)
	0.002	rainbow trout	Forteach pers comm
Dicamba	200	salmonid hatchery	SECL (1983)

Table 9.4.41 cont.

Chemical	Safe level (µg /L)	Species/Group	Source
Dieldrin	0.003	pond aquaculture species	Lannan et al. (1986)
	0.003	fish	Boyd (1990)
	<0.005	freshwater aquaculture	DWAF (1996)
	0.005	fish	Pillay (1990), Langdon (1988)
	0.003	salmon hatchery	SECL (1983)
Dalapon	110	salmon hatchery	SECL (1983)
Duthiocarbamates	<0.0001	fish culture	Langdon (1988)
Dunall OSE	<0.1	black tiger prawn	Chen (1985)
Diquat	0.5	fish	Pillay (1990)
	0.5	salmonid hatchery	SECL (1983)
	0.5	rainbow trout	Forteach pers comm
Diuron	1.5	fish	Pillay (1990)
Dursban	0.001	fish	Pillay (1990)
Endosulfan	0.003	freshwater aquaculture	Lannan et al. (1986)
	0.001	marine aquaculture	Lannan et al. (1986)
	0.01	black tiger prawn	Chen (1985)
	<0.003	freshwater aquaculture	DWAF (1996)
	<0.01	fish culture	Langdon (1988)
Endrin	0.003	salmonid hatcheries	SECL (1983)
	0.004	pond aquaculture species	Lannan et al. (1986)
	0.004	fish culture	Boyd (1990)
	0.003	fish	Pillay (1990), Langdon (1988)
	<0.002	freshwater aquaculture	DWAF (1996)
Fenitrothion	0.004	salmonid hatcheries	SECL (1983)
	0.004	rainbow trout	Forteach pers comm
	<0.2	rainbow trout	Davies et al. (1994)
	0.083	aquaculture	Eisler (1992)
	0.01	freshwater aquaculture	Lannan et al. (1986)
Gunthion (see also Azinphos-methyl)	0.01	salmonid hatchery	SECL (1983)
	0.00001	freshwater aquaculture	Schlotfeldt & Alderman (1995)
Heptachlor	0.001	freshwater aquaculture	Lannan et al. (1986)
	0.001	aquaculture	Boyd (1990)
	<0.005	freshwater aquaculture	DWAF (1996)
	0.001	salmonid hatchery	SECL (1983)
Lindane	0.01	freshwater aquaculture	Lannan et al. (1986)
	0.004	marine aquaculture	Lannan et al. (1986)
	0.02	fish	Pillay (1990), Langdon (1988)
	4.0	fish	Boyd (1990)
	<0.015	freshwater aquaculture	DWAF (1996)
	0.08	freshwater aquaculture	Schlotfeldt & Alderman (1995)
Malathion	0.01	salmonid hatchery	SECL (1983)
	<0.1	freshwater aquaculture	Lannan et al. (1986)
	0.008	fish culture	Pillay (1990), Langdon (1988)
	0.001	black tiger prawn	Chen (1985)
	<0.1	freshwater aquaculture	DWAF (1996)
	0.1	salmonid hatchery	SECL (1983)
Methoxychlor	0.1	rainbow trout	Forteach pers comm
	<0.03	freshwater aquaculture	Lannan et al. (1986)
Mexacarbate	0.03	salmonid hatchery	SECL (1983)
	0.1	fish	Pillay (1990)
Mirex	<0.001	freshwater aquaculture	Lannan et al. (1986)
	<0.001	freshwater aquaculture	DWAF (1996)
	0.001	salmonid hatchery	SECL (1983)

Table 9.4.41 cont.

Chemical	Safe level (µg /L)	Species/Group	Source
Paraquat	<0.01	black tiger prawn	Chen (1985)
Parathion	0.04 0.001 <0.004 0.04 0.04	freshwater aquaculture fish culture black tiger prawn salmonid hatchery rainbow trout	Lannan et al. (1986) Pillay (1990), Langdon (1988) Chen (1985) SECL (1983) Forteath pers comm
Pentachlorophenolate	<0.1	fish culture	Langdon (1988)
Pyrethrin	<0.001	fish culture	Langdon (1988)
Pyrethrum	0.01	fish	Pillay (1990)
Rotenone	10.0 <0.008 10.0	fish black tiger prawn salmonid hatchery	Pillay (1990) Chen (1985) SECL (1983)
Saturn	<0.033	black tiger prawn	Chen (1985)
Seagreen	<0.5	black tiger prawn	Chen (1985)
Simazine	10.0 10.0	fish culture salmonid hatchery	Pillay (1990), Langdon (1988) SECL (1983)
Silvex	2.0	fish, salmonid hatchery	Pillay (1990), SECL (1983)
TCDD (see Dioxin)			
TEPP (Tetraethyl Pyroosphosphate)	0.3	fish	Pillay (1990)
Trichlorophenol	<0.001	fish culture	Langdon (1988)
Toxaphene	0.005 0.005 0.01 <0.002 0.005 0.008	freshwater aquaculture fish fish freshwater aquaculture salmonid hatchery freshwater life	Lannan et al. (1986) Boyd (1990) Pillay (1990), Langdon (1988) DWAF (1996) SECL (1983) CCME (1993)
Zectran (see Mexacarbate)			

Note: Bolded text identifies those values recommended as water quality guidelines, * = 1/100th of 48 hr LC₅₀; † = 1/10th of 96 hr LC₅₀

Table 9.4.42 Summary of the recommended water quality guidelines for phenols

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	<0.0006–0.0017 ND	freshwater saltwater	Schlotfeldt & Alderman (1995)
General	<0.0006–0.0017	freshwater	Schlotfeldt & Alderman (1995)
Freshwater fish	<0.5 <0.001 <0.003 <0.004 <0.001	fish hatchery chlorophenols in fish culture cresol in fish culture resorcine in fish culture hydroquinone in fish culture	Pillay (1990) Svobodova et al. (1993) Svobodova et al. (1993) Svobodova et al. (1993) Svobodova et al. (1993)

ND: Not determined - insufficient information

There is insufficient information to set the saltwater guideline so either the freshwater level can be used or consider the recommendations for Aquatic Ecosystem protection (Chapter 3 of Volume 1; Volume 2).

See also Section 9.4.3 for discussion on human health aspects.

6. Polychlorinated biphenyls (PCBs)

Polychlorinated biphenyls (PCBs) were used widely as industrial chemicals and are recognised as very important environmental pollutants as they are among the most environmentally persistent of organic compounds (Svobodova et al. 1993). Although their solubility in water is very low, they are readily soluble in non polar solvents and can accumulate in fats. For these reasons and the fact that PCBs can accumulate in bottom sediments and in aquatic organisms, worldwide restrictions have been in place since the early 1970s (Zweig et al. 1999).

According to Svobodova et al. (1993), PCBs present a very difficult ecotoxicological problem: there are 209 individual PCBs, each one with different toxicological properties. They are all considered to be very toxic to extremely toxic to fish, especially in their early developmental stages. The solubility, and thus, toxicity of PCBs are enhanced by increases in temperature (Zweig et al. 1999).

Guideline notes

DWAF (1996) considers that there is no known quantitative information available on PCB levels that are *safe* and do not exert adverse effects on fish. Therefore, they say that the detection of any PCB levels should be regarded as serious. Meade (1989) suggested a level of <0.002 mg/L and this is used as the recommended guideline for both freshwater and saltwater (table 9.4.43).

See also Section 9.4.3 for discussion on human health aspects.

Table 9.4.43 Summary of the recommended water quality guidelines for PCBs

Group	Guideline mg/L	Comments	Reference
Recommended guidelines	<0.002	freshwater & saltwater	Meade (1989)
Freshwater species	0.001	freshwater aquaculture	Lannan et al. (1986)
	<0.000014	freshwater culture species	Schlotfeldt & Alderman (1995)
	0.0000011– 0.0000051	salmonids	Svobodova et al. (1993)

9.4.2.4 Pathogens and biological contaminants

As noted by Zweig et al. (1999), 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. Other ‘natural’ sources of problem organisms, including pathogens and toxic microalgae, can occur within the culture environment.

1. Algal blooms and algal toxins

Algal blooms of all types are of growing importance as water resources are under increasing use, pressure and eutrophication (addition of nutrients), and as aquaculture industries develop.

According to Zweig et al. (1999), increasing eutrophication of surface waters can cause dramatic increases in phytoplankton and aquatic macrophytes. Such a bloom can cause the water pH to rise above 10, while the collapse of the bloom and subsequent decomposition of the organic matter can result in an oxygen deficit. In addition, some algal species produce toxic substances that may affect aquatic animals as well as domestic animals and humans (table 9.4.44). Algal toxins are released into the water during the period of algal bloom, particularly when the algal cells die and decompose. The toxins can enter the aquatic animal through the gills, body surface, or through ingestion.

Table 9.4.44 Problem microalgal species in Australia and New Zealand and their effects on aquatic organisms and human consumers of aquatic foods (refer to Section 9.4.3)

Species	Adverse effect *	Source
Miscellaneous		
freshwater & marine species which form algal blooms	Anoxia, fish appetite	Handler (1996a)
Dinophyceae (Dinoflagellates)		
<i>Alexandrium angustitabulatum</i>	Proven toxin producing species, possibly conspecific with <i>A. minutum</i>	MBMB (1996)
<i>Alexandrium catanella</i>	PSP Proven toxin producing species	Hallegraeff (1991) MBMB (1996)
<i>Alexandrium minutum</i>	PSP Proven toxin producing species	Hallegraeff (1991) MBMB (1996)
<i>Alexandrium ostenfeldii</i>	Proven toxin producing species	MBMB (1996)
<i>Alexandrium</i> spp.	Possible toxin producing species (at least 27 known strains of which some strains of at least 9 species are possibly PSP-toxin producers)	MBMB (1996)
<i>Alexandrium tamarense</i>	Some strains produce PSP and one bloom caused a fish kill Toxicity to other cells prawn mortality	Hallegraeff (1991) Handler (1996a) Su et al. (1991)
<i>Cochlodinium</i> spp.	Fish kills Ichthyotoxins	Hallegraeff (1991) Handler (1996a)
<i>Dinophysis acuminata</i>	Produces okadaic acid which can cause DSP	Hallegraeff (1991)
<i>Dinophysis acuta</i>	Produces okadaic acid and dinophysis toxin-1 which can cause DSP Proven toxin producing species	Hallegraeff (1991) MBMB (1996)
<i>Dinophysis fortii</i>	Produces okadaic acid and dinophysis toxin-1 which can cause DSP	Hallegraeff (1991)
<i>Gambierdiscus toxicus</i>	CFP	Hallegraeff (1991)
<i>Gonyaulax polygramma</i>	Fish kills	Hallegraeff (1991)
<i>Gymnodinium catenatum</i>	PSP	Hallegraeff (1991)
<i>Gymnodinium</i> (Fouveaux) sp.	Proven toxin producing species	MBMB (1996)
<i>Gymnodinium mikimotoi</i>	Massive kills of benthic invertebrates and fish Gill cell toxicity, Toxicity to other cells	Hallegraeff (1991) Handler (1996a)
<i>Gymnodinium sanguinum</i> (<i>spendens</i>)	Oyster kills Physical fish and shellfish gill obstruction	Hallegraeff (1991) Handler (1996a)
<i>Gyrodinium aureolum</i> (may actually be <i>Gymnodinium mikimotoi</i>)	Gill cell toxicity	Handler (1996a)
<i>Noctiluca scintillans</i>	Fish irritant and consumer of roe Gill irritation	Hallegraeff (1991) Handler (1996a)
<i>Ostreopsis siamensis</i>	Possible CFP	Hallegraeff (1991)
<i>Pfiesteria piscimorte</i>	Ichthyotoxins	Handler (1996a)
<i>Phalacroma rotundatum</i>	Some strains produce dinophysis toxin-1 which can cause DSP	Hallegraeff (1991)

Table 9.4.44 cont.

Species	Adverse effect *	Source
<i>Prorocentrum lima</i>	Produces okadaic acid and dinophys toxin-1 which can cause DSP and possibly contributes to CFP problem Proven toxin producing species	Hallegraeff (1991)
<i>Prorocentrum minimum</i>	Possible human poisoning from eating shellfish but not DSP or PSP	Hallegraeff (1991)
<i>Prorocentrum</i> spp.	Toxicity to other cells	Handlinger (1996a)
<i>Pyrodinium bahamense</i>	PSP	Hallegraeff (1991)
<i>Ptychodiscus brevis</i> (formally <i>Gymnodinium breve</i>)	NSP	UC Davis (1997) AUST/NZ??
<i>Scrippsiella trochoidea</i>	Fish kills	Hallegraeff (1991)
Bacillariophyceae (Diatoms)		
<i>Chaetoceros convolutus</i>	Fish kills	Hallegraeff (1991)
<i>Nitzschia pseudodelicatissima</i>	Some strains produce domoic acid — causative agent of ASP	Hallegraeff (1991)
<i>Nitzschia pungens</i>	ASP	Hallegraeff (1991)
<i>Pseudo-nitzschia australis</i>	Proven toxin producing species	MBMB (1996)
<i>Pseudo-nitzschia fraudulenta</i>	Proven toxin producing species	MBMB (1996)
<i>Pseudo-nitzschia pungens</i>	Proven toxin producing species	MBMB (1996)
<i>Pseudo-nitzschia turgidula</i>	Proven toxin producing species	MBMB (1996)
<i>Rhizosolenia cf. Chunni</i>	Shellfish kills and tainting taste of seafood Toxicity to other cells	Hallegraeff (1991) Handlinger (1996a)
salicaceous diatoms	Gill irritation	Handlinger (1996a)
<i>Thalassiosira mala</i>	Oyster kills	Hallegraeff (1991)
<i>Thalassiosira</i> spp.	Physical gill obstruction	Handlinger (1996a)
Prymnesiophyceae (Golden-brown flagellates with haptonema)		
<i>Chryochromulina polyepis</i>	Fish kills Ichthyotoxins	Hallegraeff (1991) Handlinger (1996a)
<i>Phaeocystis pouchetti</i>	Fish kills Effect on fish migration, Gill irritation	Hallegraeff (1991) Handlinger (1996a)
<i>Prymnesium parvum</i>	Fish kills Toxicity to other cells, Gill cell toxicity	Hallegraeff (1991) Handlinger (1996a)
Chrysophyceae (Golden-brown algae)		
<i>Pelagococcus subviridis</i>	Lower abundance, feedings & fecundity of crustaceans and bivalves	Hallegraeff (1991)
Raphidophyceae (Chloromonads)		
<i>Heterosigma akashiwo</i>	Fish kills Toxicity to other cells	Hallegraeff (1991) Handlinger (1996a)
Dictyochophyceae (Silicoflagellates)		
<i>Dictocha speculum</i>	Fish kills	Hallegraeff (1991)

Table 9.4.44 cont.

Species	Adverse effect *	Source
Cyanophyceae (Blue-green algae)		
<i>Anabaena</i> spp.	Toxicity to other cells	Handler (1996a)
<i>Aphanizomenon</i> spp.	Toxicity to other cells	Handler (1996a)
<i>Microcystis</i>	Toxicity to other cells	Handler (1996a)
<i>Nodularia</i>	Toxicity to other cells	Handler (1996a)
<i>Trichodesmium erythraeum</i>	Nuisance organism	Hallegraeff (1991)

* Human consumers may be affected by the following : ASP = Amnesic shellfish poisoning , CFP = Ciguatera fish poisoning, DSP = Diarrhetic shellfish poisoning, NSP = Neurotoxic shellfish poisoning, PSP = Paralytic shellfish poisoning

Note : Several other possible toxin producing species known to be present in New Zealand coastal waters are listed in MBMB (1996)

Generally it is the health of finfish which is most affected by algal blooms, although there have been some instances of kills of invertebrates by them (Hallegraeff 1991, Handler 1996a). Handler (1996a) reported seven mechanisms for algal effects on fish:

- **Anoxia:** Oxygen depletion resulting from excessive abundance of phytoplankton algae is a common cause of mortality of fish and crustaceans in aquaculture ponds (Boyd 1990). Algal blooms can readily occur in water bodies with high levels of nutrients, coupled with conducive environmental conditions (e.g. no cloud and high temperatures) (DWA 1996). High concentrations of nutrients in aquaculture waters can result from overfeeding, agricultural fertiliser run-off and effluents from sewage treatment plants. Large scale aquatic animal kills from this problem have occurred in both freshwater and marine waters.
- **Physical gill obstruction:** Mucus producing species can clog the gills of fish and shellfish. Examples in Australia include *Thalassiosira* and the non-toxic *Gymnodinium sanguinenum* (*spendidens*).
- **Gill irritation:** Examples include *Phaeocystis pouchetti*, *Nitzschia* sp., *Noctiluca scintillans* and salicaceous diatoms.
- **Gill cell toxicity:** Death from the destruction of the thin gill epithelium has been caused by a number of algal species including *Gyrodinium aureolum*, *Gymnodinium mikimotoi* and *Prymnesium parvum*.
- **Toxicity to other cells:** These algae affect other cells after ingestion or absorption and are inherently more likely to affect other species following ingestion of the contaminated animals. This group includes the algae producing hepatotoxins, neurotoxins, haemolysins and digestive cell necrotoxins. Examples from Australia and New Zealand (table 9.4.44) include the blue-green algae of the genera *Microcystis*, *Aphanizomenon* and *Anabaena* (all freshwater) and *Nodularia* (generally brackish water), and the marine species *Alexandrium tamarense*, *Gymnodinium mikimotoi*, *Prymnesium parvum*, *Rhizosolenia chunii*, *Prorocentrum* spp and *Heterosigma akashiwo*.

The extent and effects of blue-green algae blooms have been summarised by Johnstone (1994). However, fish kills caused directly by the blue-green algae appear to be rare. The DWA (1996) considers that water-borne toxins produced by blue-green algae are unable to cross the gill membranes of fish and, therefore, do not enter the circulatory system. Toxic effects can be induced when the toxin is ingested by fish or when they eat the toxin-containing algal cells.

- **Ichthyotoxins:** Includes some of the above species as well as *Cochlodinium* spp, *Chrychromulina polyepis* and *Pfiesteria piscimorte*.
- **Reduced appetite:** Virtually all algal blooms, including non-toxic species, may affect fish appetite.

The effects of these toxins on the use of aquaculture products, particularly molluscs which have bioaccumulated the toxins, and the shellfish sanitation programs to overcome these problems are covered in Section 4.3. Hallegraeff (1987, 1991) provides excellent guides and detailed descriptions of many of the marine toxic species.

Handler (1996a) noted that, in general, fish which swim in waters affected by algal blooms ingest or absorb very little of these algae compared with filter feeding shellfish. In summary, she wrote there was very little overlap between the marine algal toxins accumulated by shellfish, and screened in shellfish sanitation programs, and those algal blooms causing fish kills.

Guideline notes

No guidelines can be recommended as the effects vary considerably between species of microalgae and the particular culture species.

See also Section 9.4.3 for discussions on human health aspects.

2. Bacteria, viruses and parasites

Handler (1996b) suggested that kills due to disease pose a more direct threat to the long term future of fish (cultured animal) stocks than pollutants. Water used for aquaculture always will contain a certain number of bacteria, viruses, fungi, parasites (both Protozoan and Metazoan) and other organisms which may be harmful to aquatic organisms. Even normally harmless bacteria and viruses, under adverse environmental conditions, can contribute to impaired health of the culture species. The maintenance of optimal water quality appears to be the best defence against infections by these organisms (DWAF 1996).

In artificial environs, there are means to reduce the amount of incoming potential pathogens by, for example, inflow filters that retain particles (to which most of the bacteria will be attached). In hatcheries, inflowing water may be UV-treated or ozonised to reduce the level of infective organisms. During the design of hatcheries, nurseries and growout farms, it is very important to incorporate the ability to isolate outbreaks quickly and for procedures to correct the problem.

There are many overseas examples of fish diseases which have decimated stocks rapidly after accidental introduction to native stocks or new susceptible species. Thus unusual sudden losses due to disease are more likely to represent new diseases or introductions, and rapid diagnosis of such diseases is important if they are to be controlled (Handler 1996b).

Australian examples of major diseases causing fish kills noted in Handler (1996b) include:

- Epizootic Haematopoietic Necrosis (EHN) is the classic Australian disease cause of fish kills. It is an internationally significant disease (OIE List B), only known to occur in Australia, with the very name indicating sudden mortalities. Most outbreaks are in Redfin perch, but has also been diagnosed in small rainbow trout. The distribution within Australia is limited, which makes knowledge of the distribution at any time important for control of fish movements, to prevent the spread of EHN to uninfected areas.
- Another serious disease of limited distribution in Australia is the Goldfish atypical strain of *Aeromonas salmonicida*, which was introduced into Australian Goldfish breeding

stocks in 1970s, and has since spread in to wild Goldfish, and to some other fish species. Usually a low death rate, occasionally high level of skin lesions.

- Epizootic ulcer syndrome (EUS), Red Spot disease, Bundaberg disease etc, from a range of species. Low mortality, high morbidity (ulcers), with a wide geographic range.

Handler (1996b) also noted that disease may be only one component in a complex cause of death, often acting in conjunction with environmental or physiological stress factors. Examples include:

- The gill protozoan *Chilodonella* or the skin fungus *Saprolegnia sp* cause deaths in Bony Bream (*Nematalosa erebi*) when winter temperatures fall below 10°C *Chilodonella* species are also thought to be introduced to local wild stocks through imported fish.
- Winter deaths with Saprolegniasis (fungus infection of skin) in brown trout with spawning stress associated with crowded spawning grounds in Tasmania.
- Eel Saprolegniasis deaths in post capture holding facilities following capture (crowding stress).
- Septicaemia in stressed migrating lampreys after trauma from obstacles to migration.
- Large number of digenean flukes in the gills and peritoneal cavity of Galaxids dying in saline lakes in 1984. Major cause of death probably a bloom of the dinoflagellate *Glenodinium*. Dying Redfin perch from the same area showed large numbers of the bacterium *Aeromonas hydrophila*.

The identification and treatment of pathogenic problems is outside the scope of this Chapter. A wide range of literature is available on this subject, some of which is listed below:

- finfish — PGVSUS (1988, 1992, 1996), Wolf (1988), Sindermann (1990), Austin & Austin (1993), Schlotfeldt & Alderman (1995)
- molluscs — Elston (1990), Sindermann (1990)
- prawns — Lightner (1996)
- freshwater crayfish — Huner (1994)

Guideline notes

No guidelines can be recommended as the effects vary considerably between species of pathogen and the particular culture species.

In summary, a reduced level of infectious organisms will contribute to a better overall health of aquaculture animals, a reduced need to treat animals with chemicals and drugs and, thus, to lower production costs as well as a residue-free product.

See also Section 9.4.3 for discussions on human health aspects.

9.4.3 Water quality guidelines for the protection of human consumers of aquatic foods

Most aquaculture products and recreationally and commercially harvested aquatic species are destined for consumption by humans. Generally aquaculture and commercially harvested aquatic foods are considered gourmet items and attract a premium price. To maintain demand, the aquaculture and fishing industries must ensure the highest quality of these products, both from a visual and, most importantly, from a human health point of

view. The guidelines contained in this Section are intended to protect the health of human consumers of aquatic foods.

A range of chemical and biological contaminants (including bacterial and viral pathogens) are of concern (table 9.4.45). These may accumulate in the soft tissues of aquatic species through ingestion. Other toxicants can be taken up by the animals directly from the water source through passive diffusion or active uptake. While these contaminants may not be deleterious to the health of the organisms concerned, many can adversely affect human health if consumed above certain levels. Others can taint, or cause 'off-flavour', which affects the palatability of aquatic foods and lower their market acceptability.

Table 9.4.45 Chemicals and biological contaminants important for the protection of human consumers of fish and other aquatic organisms (based on University of California, Davis, website, 1997, Cunliffe pers comm and Jackson pers comm)

Contaminants	Types
Chemical contaminants	Inorganic chemicals (heavy metals, etc.)
	Organic chemicals (pesticides, etc.)
	Radionuclides (radioactive elements)
Viral contaminants	Hepatitis A
	Norwalk virus
	Parvo-virus
	Poliovirus
	Rotavirus
Bacterial contaminants	<i>Listeria monocytogenes</i>
	01 <i>Vibrio cholerae</i>
	Non 01 <i>Vibrio cholerae</i>
	<i>Vibrio parahaemolyticus</i>
	<i>Vibrio vulnificus</i>
	<i>Vibrio mimicus</i>
	<i>Vibrio hollisae</i>
	<i>Salmonella</i> sp
shiga toxin producing <i>E. coli</i>	
Natural Toxins	Ciguatera
	Paralytic shellfish poisoning
	Neurotoxic shellfish poisoning
	Diarrhetic shellfish poisoning
	Puffer fish toxicity (tetrodotoxins)
Parasites	<i>Anisakis simplex</i> or herring worm
	<i>Clostridium perfringens</i>
	<i>Shigella</i>
	Enterotoxic <i>E. coli</i>
	<i>Cryptosporidium</i> sp
	<i>Giardia</i> sp

The food standards developed by the Australian and New Zealand Food Authority (ANZFA) and published in the *Food Standards Code* (ANZFA 1996) aim to protect consumers from eating chemically contaminated foods, including aquatic species ((also see Australian web site (www.anzfa.gov.au) and New Zealand web site (www.anzfa.govt.nz) for updated information). These are based on the notion of acceptable daily intake (ADI) or acceptable weekly intake (AWI) — see Zweig et al. (1999) for the World Health Organization (WHO) provisional tolerable weekly intake for selected elements as well as import regulations for residues.

The food standards apply to the edible portion of the organisms, so the flesh levels, not the levels in the liver, kidney or other organs which are usually higher, are specified for finfish, while the hepatopancreas levels are not included for crustaceans (although this organ is eaten by some consumers). With molluscs, the parts consumed varies from the whole animal (e.g. oysters, clams and mussels) to specific parts (e.g. abalone, scallops and cephalopods).

9.4.3.1 Physio-chemical parameters

The basic physio-chemical properties of waters, whether natural or in artificial environs, generally do not have any direct effects on the safety of human aquatic foods during the culture (growing) or harvesting processing. However, post harvest activities need to be undertaken at the appropriate temperatures to avoid spoilage of the end product.

9.4.3.2 Chemical contaminants

As detailed in table 9.4.45, chemical contaminants may be categorised into three broad groups:

- **Inorganic chemicals (mostly heavy metals):** These are a potential problem for human health, particularly in the case of bivalve molluscs where bioaccumulation increases the concentrations of toxicants. The rate of accumulation is species specific and depends on the mechanism of absorption and tissue distribution.
- **Organic chemicals (e.g. pesticides and herbicides):** This broad group includes synthetic compounds which through either bioaccumulation or residue concentrations are potentially toxic to human consumers of contaminated aquatic foods.
- **Radionuclides (radioactive elements):** At present, ANZFA do not give any maximum permitted concentrations (MPCs) for radionuclides in edible tissues. Many countries have limits set on imported foods, particularly for cesium-137 (Cs-137). Environmental levels of Cs-137 are considerably lower in the southern hemisphere than in the northern hemisphere, and exporters in Australia and New Zealand should not generally experience difficulty in meeting such limits.

The ANZFA food standards should be considered as the default standards for chemical contaminants. As the standards are currently under review, readers are referred to the relevant Australian (www.anzfa.gov.au) and New Zealand (www.anzfa.govt.nz) ANZFA web sites for updated information.

Zweig et al. (1999) provide an excellent summary of the guidelines used by the United States, Canada, Japan and the European Union for a wide range of chemical contaminants residues in imported aquatic foods.

9.4.3.3 Biological contaminants

There are a number of biological contaminants which can affect human consumers of aquatic foods, including:

- bacteria;
- viruses;
- parasites;
- micro-algae (biotoxins).

For each of these groups, further discussion is provided in the next four Sections (9.4.3.3/1–4). Various approaches for prevention and management of these potential contaminations are provided in Section 9.4.3.5.

The flesh of fish and crustaceans is less susceptible to contaminations by microorganisms and biotoxins. However, filter-feeding shellfish (bivalves) can concentrate these potential contaminants to levels higher than that in the water source. Thus shellfish are considered to be a higher risk for consumers of aquatic foods, although there can be secondary problems associated with fish or crustaceans, for example poisoning from wounds inflicted when handling these animals.

Table 9.4.46 specifies guidelines on safety for human consumption for the micro-algal biotoxins which use levels of toxins in edible flesh, note that in Australia there are no standards for NSP or DSP. For bacterial organisms the guidelines for commercially harvested fish species are based on risk management programs and vary between countries (Section 9.4.3.5/2). A water quality guideline for minimising the exposure of human consumers to bacterial diseases caused by ingesting contaminated wild fish species is provided in Section 4.4.5.3 of the Guidelines (Volume 1).

Table 9.4.46 Guidelines for the protection of human consumers of shellfish and finfish from contamination by microalgal biotoxins

Toxicant	Guideline <i>in water</i>	Standard <i>in edible tissue</i>
Neurotoxic shellfish poison (shellfish only)	No guideline. Toxins may be present in the microalgae and may be accumulated in other aquatic organisms.	<20 mouse units/100 g of edible shellfish flesh [New Zealand only]
Diarrhetic shellfish poison (shellfish only)	No guideline. Toxins may be present in the microalgae and may be accumulated in other aquatic organisms.	<20 µg/100 g of edible shellfish flesh (~5 mouse units) [New Zealand only]
Paralytic shellfish poison (shellfish only)	No guideline. Toxins may be present in the microalgae and may be accumulated in other aquatic organisms.	<80 µg of saxitoxin equivalent/100 g of edible shellfish flesh (~400 mouse units) [Australia & New Zealand only]
Amnestic shellfish poison (shellfish only)	No guideline. Toxins may be present in the microalgae and may be accumulated in other aquatic organisms.	<20 µg/g of domoic acid in edible shellfish flesh [Australia & New Zealand only]
Ciguatera-like toxins (finfish only)	No guideline. Toxins may be present in the microalgae and may be accumulated in other aquatic organisms.	<20 mouse units/100 g shellfish [New Zealand only]

Source: MBMB (1996) and Jackson (pers comm).

1. Bacteria

Bacterial aquatic food borne diseases in humans can be grouped according to where the bacteria originate:

- bacteria that are present in water/sediments (e.g. *Clostridium botulinum*; *Vibrio parahaemolyticus*; other *Vibrio* spp);
- bacteria from pollution of aquatic environments with human and/or animals faeces (e.g. *E. coli* and enterotoxic species, *Clostridium perfringens*, *Vibrio cholerae*; *Salmonella typhi*; other *Salmonella* spp; *Shigella flexneri*).

Bacterial contamination of aquatic foods can occur from exposure within the aquatic environment and/or after harvest and during processing. The latter is not within the scope of this document. However, most cases of human disease (gastroenteritis) are associated with consumption of raw or undercooked molluscs which have been contaminated either immediately or shortly prior to harvest.

For commercial harvesting of shellfish the usual approach to reduce the bacterial load to control this human health hazard is two-tiered:

- risk based (i.e. it is the risk level that defines the classification status) classification of waters (Section 9.4.3.5 No.2) to allow only certain waters/times for rearing/harvesting of molluscs for human consumption, based on results of detailed sanitary surveys and an ongoing strategic monitoring program which assesses growing water and shellfish quality (this approach includes the relaying of contaminated stock to clean waters and depuration, see below);
- treatment of shellfish to render safe for consumption e.g. heat treatment or irradiation of molluscs if necessary.

Depuration was formally introduced in NSW following a food poisoning outbreak in 1978, involving over 2000 clinical cases of viral gastroenteritis which was attributed to the consumption of contaminated shellfish farmed in the Georges River (Linco & Grohmann 1980, Murphy et al. 1979). Prior to this outbreak there was little information available regarding the sanitary status of NSW estuaries. From 1978 to 1981, estuaries where oysters were farmed in NSW were sampled by regulatory authorities in an attempt to ascertain the levels of faecal contamination. On the basis of these bacteriological findings estuaries were ranked according to risk, however, the methodology used in the sampling regime resulted in errors in the ranking of estuaries, with some estuaries being sampled at low frequency and consequently ranked incorrectly (Ayres 1991). Depuration was initially introduced to estuaries identified as high risk and by 1983 depuration of all shellfish sold in NSW became a statutory requirement, regardless of the sanitary status of the estuary from where the shellfish were harvested (Jackson & Ogburn 1998). Currently depuration remains compulsory for all oysters harvested in NSW for human consumption, however, this requirement is currently being reviewed as oyster harvest areas are assessed in terms of risk and formally classified.

Depuration is a process which exploits the natural physiological mechanisms of shellfish to promote purging of the gastrointestinal tract. Shellfish are depurated in order to reduce the likelihood of transmitting infectious or other injurious agents to consumers. Depuration involves live animals and the success of the process is dependent on the well being of these animals. The efficacy of depuration may be defined as the extent to which microbial and other contaminating agents are eliminated from shellfish during the process.

According to Jackson and Ogburn (1998) the current status of depuration and the factors which affect the efficacy of the process for bacterial species (refer to 9.4.3.3 No.2 for viruses) include:

- Depuration, under appropriate operating conditions, is capable of removing many bacterial species from shellfish, including faecal coliforms.
- The water temperature, salinity and turbidity all influence the efficacy of depuration. These factors must be optimised to maintain the health status of the shellfish in order to maximise the efficacy of depuration.
- It is likely that the optimal conditions for depuration will vary between shellfish species and within a species which has been acclimatised to different environments.
- The initial pathogen load, length of exposure to the pathogen and pathogen distribution within shellfish tissues will each influence the efficacy of depuration. Generally, the efficacy of depuration is decreased when the initial pathogen load is high.
- Ultraviolet radiation as a means of water disinfection during depuration, is relatively efficient and cost-effective. Further research is required to assess methods to enhance UV disinfection and to investigate alternate methods of disinfection.
- Not all bacterial species are removed from shellfish at the same rate during depuration. It is apparent that bacteria that constitute part of the natural microbiota of the shellfish (e.g. *Vibrio* spp.) are less readily removed than introduced bacteria (e.g. *E. coli*).

Zweig et al. (1999) provide an excellent summary of the guidelines used by the United States, Canada, Japan and the European Union for a wide range of bacteriological standards in imported aquatic foods. For further discussion on *Listeria monocytogenes* and the various *Vibrio* spp, refer to UC Davis (1997).

2. Viruses

Viruses that infect human consumers of aquatic food or diffuse sources such as on-site wastewater systems (e.g. septic tanks) are of human origin (i.e. these viruses have been shed in human faeces via sewage outlets into waters where aquatic organisms are cultured or harvested). There are more than 110 different viruses known to be excreted in human faeces, collectively known as the 'enteric viruses' (Goyal 1984). They can remain in seawater for long periods of time and have been shown to survive as long as 17 months in marine sediments (Goyal et al. 1984). UC Davis 1997 suggests that viruses that are associated with sediments are as infectious to animals as those that are freely suspended, however, the potential exposure routes were not identified. However, there is a question regarding the infectivity of these agents whilst in waters and sediments, as pieces of viral RNA/DNA detected by some methods might not actually infer the presence of viable cells, see Richards (1999) for a discussion of this issue.

Viruses have been isolated from a wide range of bivalve molluscs whose filter-feeding activities can concentrate the viruses at levels much higher than the surrounding waters. The viruses do not multiply in bivalves, but accumulate in the gastrointestinal tract, liver-like digestive gland and other tissues. The behaviour of these agents is very complex and the accumulation rate is dependent on the viral species and the species of mollusc. Crustaceans, such as crabs and lobsters, can accumulate viruses by contact with contaminated seawater and/or by consuming contaminated bivalves (Hejkal & Gerba 1981). Whilst the highest concentration of viruses are found in the inedible portions of crabs (Goyal et al. 1984), they are usually present at a level below that of the water (UC Davis 1997).

Many cases of human food poisoning outbreaks have been associated with the consumption of contaminated raw oysters. In 1978, 1989 and 1990 Norwalk virus and Parvo-virus were responsible for three major food poisoning outbreaks in Australia, while the cause of another outbreak in 1996 was unconfirmed but could have been Norwalk virus. In 1997 an outbreak of Hepatitis A was linked to the consumption of contaminated oysters.

The presence or absence of viruses is even more difficult to detect than bacteria, so indicator species are also used. Since the viruses of concern to human health are derived mainly from sewage, *E. coli* and other faecal coliforms are used as the indicator species. However, the correlation between the presence of faecal coliform and viruses is unreliable. It is also now thought that shellfish may eliminate *E. coli* from their systems without eliminating viruses, so the absence of *E. coli* in the flesh is not a satisfactory predictor of absence of viruses. Nevertheless, the use of sanitary surveys are still relevant and are used in Australia and New Zealand as well as the USA and European Union (see Section 9.4.3.5 No.2).

Heat and depuration — which work well to reduce bacterial contamination of molluscs — are not equally efficient in reducing viral loads. Heat treatment may need to take place at higher temperatures than required for bacteria. UC Davis (1997) indicate that most viruses (excluding Hepatitis A) are inactivated when the internal temperature of molluscs reaches 60°C (140°F), which requires some 4 to 6 minutes of steaming. A common cooking practice is to steam molluscs only until the shell opens, however, as this may occur after only 1 minute of steaming (UC Davis 1997), this is not sufficient time to inactivate all of the viruses.

The ability of depuration to effectively eliminate viral agents from shellfish is uncertain. It is apparent that viral agents are capable of remaining in shellfish after the depuration process, and that viral agents generally take a longer period of time compared to bacteria, to be effectively removed from shellfish (Jackson & Ogburn 1998). Further research is required in this area.

Jackson and Ogburn (1998) provide a good review on the subject. For further discussion on Hepatitis A, Norwalk virus and Poliovirus, refer to UC Davis (1997).

3. Parasites

To date there is no evidence in Australia or New Zealand of any parasites which can be passed from aquatic organisms to humans, therefore no guidelines are provided. There is little epidemiological evidence indicating an important role of shellfish in the dissemination of protozoan infections, but *Giardia* sp. and *Cryptosporidium* sp. remain possibilities (Stelma & McCabe 1992). Fayer et al. (1998) indicated that oysters can serve as mechanical vectors of the human pathogen *Cryptosporidium parvum* oocysts.

Furthermore, it should be noted that the presence of parasites, cysts and necrotic tissue resulting from parasitic infections is likely to make the product unmarketable.

4. Marine biotoxins

There are a number of marine biotoxins which represent a significant threat to human consumers of aquatic foods — they are mostly associated with microalgae, although there are some toxins which occur in species which do not involve marine algae.

Microalgal-associated toxins

A comprehensive review of this topic is provided by Hallegraeff (1991). There are five recognised types of toxins (see table 9.4.46), which are all associated with naturally occurring marine microalgae (table 9.4.44 in Section 9.4.2.4/1 provides a list of problem

species in Australia and New Zealand). The toxins can accumulate in aquatic animals when they feed on the algae or on other animals which have fed on the algae. They include:

Paralytic shellfish poisoning (PSP)

- A number of toxic dinoflagellates can be concentrated by filter feeding bivalves and become poisonous to humans, these include species of *Gonyaulax*, *Gymnodinium*, *Alexandrium* and *Pyrodinium*. These are often described as the 'red tide' species due to the colouring of the water when they occur in blooms, although the colour is not always red. They are found in a wide range of environments from tropical to temperate waters.
- PSP can be caused by a combination of any of 18 toxin analogues, depending on the species of dinoflagellate and geographic area (UC Davis 1997). The primary toxins include saxitoxins, gonyautoxins and derivatives.
- All filter-feeding molluscs accumulate and depurate paralytic shellfish toxins (UC Davis 1997). In the Northern Hemisphere (USA), PSP has been reported in the viscera of mackerel, lobsters and crabs (UC Davis 1997).
- In 1986 a bloom of *Gymnodinium catenatum* caused two cases of poisoning from consumption of wild mussels and oysters in Tasmania (Jackson pers comm). Routine monitoring of this biotoxin group is undertaken in New Zealand.

Diarrhetic shellfish poisoning (DSP)

- Several dinoflagellates of the *Dinophysis* and *Prorocentrum* genera have been associated with DSP (refer UC Davis 1997).
- To date eight lipid soluble toxins have been isolated, including okadaic acid, dinophysistoxins, pectenotoxins, yessotoxins and derivatives. Filter-feeding molluscs can accumulate these toxins in their hepatopancreas even at dinoflagellate concentrations below that necessary to discolour the water (UC Davis 1997).
- DSP cases have been reported from commercial harvests of wild pipis in south Ballina Beach and Stockton Beach in NSW (Jackson, pers. comm.). Routine monitoring of this biotoxin group is undertaken in New Zealand.

Amnesic shellfish poisoning (ASP)

- Diatoms from the genus *Pseudonitzschia* produce the neurotoxin known as domoic acid (an amino acid) which also accumulates in filter-feeding shellfish (Handlinger 1996b). In the Northern Hemisphere (USA) PSP has been reported in the viscera of anchovies and crabs (UC Davis 1997).
- No evidence to date of occurrence in Australia, however, routine monitoring for this biotoxin group is undertaken in New Zealand.

Neurotoxic shellfish poisoning (NSP)

- *Ptychodiscus brevis* (formally *Gymnodinium breve*) can produce three known toxins called brevetoxins: brevetoxin B, brevetoxin C and GB-3 (Yasumoto 1985).
- No evidence to date of occurrence in Australia, however, routine monitoring for this biotoxin group is undertaken in New Zealand.

Ciguatera fish poisoning (CFP)

- By ingesting toxic dinoflagellates, certain species of tropical and subtropical fish can become toxic to humans.

- The species most often associated with ciguateric fish is *Gambierdiscus toxicus*. Other algal species include *Ostreopsis* spp. and *Prorocentrum* spp.
- There are at least four known toxins: ciguatoxin (the principal toxin), scaritoxin, ciguaterin and maitotoxin (UC Davis 1997).
- The toxins appear to be concentrated in the viscera, head or central nervous system of affected fish (Tosteson et al. 1988).
- Both herbivorous and carnivorous fish can become toxic, the first group by eating the algae itself, the second group by consuming toxic herbivorous fish. Generally larger fish are more poisonous than small fish as they consume greater amounts of toxins (Graig 1980). In Australia the fish most implicated in cases of ciguatera include mackerel and barracuda. The harvest waters in New Zealand are too cold for this biotoxin group.

Other toxins

According to UC Davis (1997), there are three naturally occurring species which are found in species that do not involve marine algae:

- **Gempylotoxin:** this is found in the escolars or pelagic mackerel, a small group of fish-eating oceanic fish as well as the snoek *Thyrsites atun*. In Australia the mackerel species of concern include *Lepidocybium flavobrunneum* and *Ruvettus pretiosus*. They produce an oil which has a purgative effect. No problems have been reported for this biotoxin group in New Zealand.
- **Tetramine:** this toxin is found in the salivary glands of the welk *Neptunia*, which is not found in Australia or New Zealand.
- **Tetrodotoxins:** there are 80 species of puffer (also called fugu or blowfish) fish that are known to contain the neurotoxin tetrodotoxin, some occur in Australian waters. It is unclear whether the fish itself produces the toxin, or like ciguatoxin, it is introduced to the fish by eating toxic algae.

Further information

For a detailed discussion of the biotoxin situation in New Zealand refer to MBMB (1996) whilst ASSAC (1997) provides a some brief notes for Australia. Details on symptoms and treatment, detection and prevention and selected bibliography for each of these toxins refer to UC Davis (1997).

9.4.3.4 Off-flavour compounds

Off-flavour compounds, otherwise known as tainting substances, can seriously affect the palatability of fish, crustaceans and molluscs and therefore have a large deleterious impact on the aquaculture and wild-capture fishing industries (both commercial and recreational). According to Zweig et al. (1999) odorous organic compounds, such as those from petroleum distillates and paper processing and other industrial effluents, are a common source of off-flavours in fish.

Table 4.4.5 in Volume 1 identifies a variety of off-flavour compounds together with the threshold concentration at which tainting will occur.

Svobodova (1993) suggested the admissible concentrations for a range of off-flavour causing contaminants:

- oils range between 2 and 25 µg/L

- chlorophenol is 1 µg/L
- cresol is 3 µg/L
- resorcine is 4 µg/L
- hydroquine is 1 µg/L

According to Zweig et al. (1999), the simplest test for off-flavour producing organics requires neither equipment nor reagents: water which tastes or smells unusual may result in off-flavour. Therefore a sensory assessment can often be preferable to chemical analysis in assessment of the source water.

In addition to the chemical contaminants, a number of freshwater blue-green microalgae (cyanophyceae) and bacteria (actinomycetes) can cause off-flavours in native fish. The most common is the earthy/musty flavour, often referred to as 'muddy' taste, which often occurs in silver perch (*Bidyanus bidyanus*). Rowland (1995b) reported that the majority of off-flavour episodes are caused by geosmin and 2-methylisoborneol compounds which are rapidly absorbed by fish and stored predominantly in fat tissue. Decaying organic matter can also cause off-flavour. The incidence of these off-flavours is highest in warmer months, during blooms of blue-green algae and in ponds with high stocking and feeding rates. Most off-flavours can be readily purged by placing fish in clean water such as underground or spring water, domestic (dechlorinated) or rainwater. Rowland (1995b) recommended that fish be purged in a solution of 3 g/L NaCl for at least 7 days.

9.4.3.5 Preventative and management approaches

There are usually high costs associated with detecting the levels of chemical and/or biological contaminants, either in the flesh of the aquatic organisms or in the waters in which they occur. It is generally accepted that food species should not be grown in, or harvested from, waters likely to be exposed to contamination. If a contamination should occur, the aquatic organisms should be regularly analysed to ensure that the ANZFA standards are not exceeded in harvested product.

Excluding filter-feeding shellfish where testing generally takes place prior to harvest (see below and Section 9.4.3.5 No.2), a problem with other types of aquaculture/fishery product testing is that it is retrospective. For planning purposes a method of product quality prediction would be preferable. This problem may be illustrated by the following examples:

- The viability of the setup of an aquaculture business is being investigated. How can the investors predict whether, on harvesting, the product will be suitable for sale for human consumption?
- It is proposed to start up an industrial/sewage plant upstream of a commercial fishery. How can we predict whether effluent from the plant will have a significant adverse effect on the fishery product quality?

Section 9.4.3.5 No.1 gives a simplified approach to making predictions of this nature using the *bioconcentration factor* approach. Since circumstances will vary enormously from case to case, this approach is only intended as a general guide, not as a set of prescriptive rules. In addition, because of the complexities involved, uncertainties will be associated with any prediction. Predictions cannot replace product testing. However, they may enable problems to be identified and resolved before they impact on an industry.

The testing of flesh samples (particularly for filter feeding species) to monitor growing area conditions provides a better indicator of long-term growing area water quality than an instantaneous grab water sample — water samples are useful for tracking pollution or for monitoring trends over a long period of time, however, the value of this type of sampling is of course related to the number of samples collected (i.e. spatial and temporal). This *area classification* approach is discussed in Section 9.4.3.5/2. The use of routine *monitoring for phytoplankton* is outlined in Section 9.4.3.5/3. Another preventative or management option is the *three-phased screening* approach, suggested by Zweig et al. (1999), is provided in Section 9.4.3.5/4.

1. Bioconcentration factor approach

One of the simplest methods of predicting bioaccumulation is the *bioconcentration factor* approach. Numerous terms are used in the literature for the same or related concepts, including *concentration factors*, *bioaccumulation factors* and *concentration ratios*.

Basic principles

Organisms obtain chemicals from a variety of sources in their environment, such as water, food, sediment, etc. The uptake of many chemicals is not homeostatically controlled by the organism's metabolism. If this is the case, then a higher concentration of the chemical in the source should result in a higher concentration in the organism. In fact, the bioconcentration factor approach assumes that the concentration in the organism which is attributable to a given source is *proportional* to the concentration in the source. In this case, the constant of proportionality is called the bioconcentration factor. For example, if C_f^w is the concentration of a chemical in a fish's flesh due to uptake of that chemical from the water in which it lives, and if C_w is the concentration of the chemical in the water, then the bioconcentration factor F^w may be calculated as follows:

$$F^w = \frac{C_f^w}{C_w}$$

If C_f^w and C_w are in the same units (for example, mg/kg), then F^w will be a simple number without units.

In some cases, it may be possible to make the further simplification that the concentration in an aquatic organism is directly related to only one source: the water in which it lives. This may be the case if the organism is known to take up the chemical almost exclusively from the water, or if it can be assumed that any changes in concentrations in the water will also result in proportional changes in concentrations in other sources such as food, sediment, etc.

Example 1

A fish used in aquaculture is known to bioaccumulate a chemical from two sources: water and food. The bioconcentration factors have been determined to be 10 and 30, respectively. If the concentration in the water² (C_w) is 0.01 mg/kg, and the concentration in the feedstock (C_F) is 0.005 mg/kg, then we can predict the concentration in the fish to be:

$$C_f = C_f^w + C_f^F = (F^w \times C_w) + (F^F \times C_F) = (10 \times 0.01) + (30 \times 0.005) = 0.25 \text{ mg/kg}$$

² For water, concentration units of mg/kg and mg/L are equivalent.

Example 2

A fishery has been harvesting from a river floodplain area, and has collected water and product quality data over a long period. The harvested fish are restricted to the floodplain area over their lifetime. A factory is proposed to be built upstream, resulting in discharges of lead to the river. It is predicted that other water quality parameters will not be significantly affected by the factory, and that the *increase* in lead concentrations in floodplain waters resulting from the factory will be 0.01 mg/L (total water).

Based on their historical data, the fishery determines that the average bioconcentration factor F^w for lead in harvested product from the floodplain is 200 relative to total water, and that the average concentration of lead in the water (without the factory being present) is 0.003 mg/L. Using the bioconcentration factor, we can predict that the average concentration in product (C_p) after the factory is operating will be:

$$C_p = F^w \times C_w = 200 \times (0.003 + 0.01) = 2.6 \text{ mg/kg}$$

Since this is higher than the limits for lead in fish (1.5 mg/kg, table 9.4.46), the restrictions on effluent release from the factory may need to be significantly tighter than those proposed.

Some difficulties with using the bioconcentration factor approach

The bioconcentration factor approach attempts to model complicated bioaccumulation processes using a simple ratio. Caution must be exercised when using the approach, particularly when some of the basic assumptions of the method may not apply to the specific case being investigated. Some of the potential difficulties and limitations of the approach will be discussed in the following.

Assumption that the chemical is not homeostatically controlled

The bioconcentration factor approach should not be used for chemicals which are homeostatically controlled by the organism. In particular, it should not be used for essential elements (e.g. Co, Cu, Fe, Mn, Mo). For these elements, an organism's metabolism can be expected to maintain a constant flesh concentration regardless of the concentration in the water, up to the point at which an overload occurs (Chapman et al. 1996).

Identification of the appropriate source for calculation of bioconcentration factor

The bioconcentration factor used should relate the concentration in the aquatic organism to that source (e.g. total or filtered water concentration) which is the best indicator of uptake of the constituent in question.

Tissue distribution and the use of a bioconcentration factor for the appropriate product

Because most contaminants will bioaccumulate to a different extent in different tissues, the bioconcentration factor must relate to the tissue which is to be sold for consumption (muscle flesh, whole fish, etc).

Effect of water quality on bioconcentration factor

General water quality parameters, such as temperature, pH and major ion and suspended solids concentrations, can affect the bioconcentration factor. For example, in one study of polychlorinated biphenyl (PCB) in sunfish, the bioconcentration factor increased from 6000 to 50 000 between 5 and 15°C (Barron 1990).

Increasing concentrations of major ions with similar chemistries to that of the trace contaminant may lead to lower bioconcentration factors. For example, for freshwater fish

higher potassium concentrations can result in lower bioconcentration factors for cesium, while higher calcium concentrations can result in lower bioconcentration factors for strontium (NCRP 1984).

Assumption of steady state between tissue and water concentrations

The bioconcentration factor approach assumes that a steady state condition has been reached between concentrations in the edible tissue of the organism and concentrations in the source. Once this steady state is attained, the rate of uptake of a contaminant by the tissue equals the rate of loss (i.e. excretion) by that tissue. In reality, this only applies when the rates of uptake and loss are fast, so that a steady state condition is reached in a short time relative to both the lifetime of the aquatic organism and to the time scales over which changes in concentrations in the source occur.

On the other hand, when the uptake and loss rates are slow, then the aquatic organism will accumulate the contaminant gradually over its lifetime. In such a case, the bioconcentration factor approach may still prove useful *provided* that the bioconcentration factor has been determined using concentrations in aquatic organisms which were of the same age as those which are to be harvested, and that the water concentrations used are average concentrations determined over the lifetime of the aquatic organism.

Captive/non-mobile vs. mobile populations

Bioaccumulation predictions are likely to be most reliable in situations where the organism is captive or non-mobile (e.g. as for aquaculture and for sedentary species such as mussels), because the water quality to which they are exposed may be more accurately and reliably determined than for more mobile populations.

Obtaining concentration factors

Given the above complications, locally-derived bioconcentration factors are to be preferred where they are available. Unfortunately, collecting the necessary data can be a time-consuming and expensive exercise.

In the case of organic chemicals, measurement of the chemical partitioning between water and the organic chemical octanol is commonly used to estimate bioconcentration factors. Although there are some complications with this approach (Barron 1990, Meylan et al. 1999), it is less expensive than the measurement of the bioconcentration factor itself.

Where a locally-derived factor is not available, relevant literature values will need to be obtained. Some databases of bioconcentration factors exist, such as the USEPA's AQUIRE database (USEPA 1995). Generic guideline factors for a number of elements are also available from IAEA (1994).

Uncertainties in bioconcentration estimates

The accuracy of any prediction using bioconcentration factors will depend upon a large number of parameters. In general, accuracy better than an order of magnitude (i.e. a factor of ten) should not be expected, and the situation may be considerably worse than this where, for example, only generic guideline bioconcentration factors are available.

Further information

Barron (1990) discusses factors affecting bioconcentration of organic chemicals.

Walker and Gobas (1999) discuss the use of bioconcentration factors to derive water quality guidelines, particularly for organic chemicals.

Chapman et al. (1996) discuss bioaccumulation estimates for essential metals.

IAEA (1994), ICRP (1978) and NCRP (1984) give general information on methods of bioaccumulation estimation, with an emphasis on bioaccumulation of radioactive elements.

2. Area classification approach

The Australian and New Zealand Area Classification Approaches (described below) are heavily based on the USFDA program (also described below).

Australia

The Australian Shellfish Quality Assurance Program (ASQAP), formerly called the Australian Shellfish Sanitation Control Program (ASSCP), was introduced in 1988 in response to needs of the emerging Tasmanian oyster industry and AQIS (Australian Quarantine Inspection Service). In addition it was recognised that many Australian shellfish growing areas were under increasing pressure from a range of human activities including discharge of untreated or poorly treated human wastes, direct industrial waste discharge and runoff from urban and agricultural areas. to comply with export requirements.

The objectives of the ASQAP include:

- control the harvesting of contaminated shellfish by identifying and evaluating the impact of pollution of shellfish growing waters;
- protect shellfish from contamination after harvesting (post-harvesting controls).

A major component of the ASQAP is the identification of safe shellfish growing areas to permit commercial harvesting for the domestic market and/or for export. It should be noted that this program is not compulsory in any way and the degree to which the program is implemented varies amongst the states. While most states do not differentiate between domestic and export product, some have no legislative force behind their domestic sales. In addition, there is difficulty in applying the program to non-farmed shellfish in some states. For these reasons, the ASQAP is currently under review.

The ASQAP Operations Manual (ASSAC 1997) provides authorities interested in shellfish sanitation with a risk based system of procedures and guidelines to be used when regulating shellfish growing areas, harvesting, processing and distribution of shellfish. It covers:

- classification and survey of growing areas;
- relaying (relocation) and harvesting controls;
- post-harvest handling, storage, processing and transportation.

The shellfish harvesting area classification systems used in the ASQAP rely on the Sanitary Survey approach to ensure that molluscan shellfish harvested for human consumption are safe. The Sanitary Survey consists of:

- the identification and evaluation of all potential and actual pollution sources (Shoreline Survey) — this describes the studies required to identify and quantify pollution sources and estimate the movement, dilution and dispersion of pollutants in the receiving environment;
- the monitoring of growing waters and shellfish to determine the most suitable classification for the shellfish harvesting area (Bacteriological Survey) — this refers to the measurement of faecal indicator levels in the growing areas.

Resurveys are conducted regularly to determine if sanitary conditions have undergone significant change. They provide the basis for the classification of coastal and estuarine areas for the harvesting of clams, oysters, scallops, mussels and other bivalve molluscs.

As *Escherichia coli* (*E. coli*) is present in faeces and is not a normal constituent of the environment, the presence of *E. coli* (nonpathogenic strains) is used as an indicator of faecal contamination of food and water. The presence of *E. coli* in food or water suggests that enteric pathogenic bacteria may be also present. According to Jackson and Ogburn (1998) bacteria commonly used as indicators of faecal contamination include:

1. *Escherichia coli*.
2. Faecal coliforms. A less restrictive test that is quicker to perform and includes intestinal bacteria including *E. coli*.
3. Total coliforms. The least restrictive test that demonstrates the presence of bacteria from the intestine, as well as some related species of bacteria normally found in the environment.

It is pertinent to note that these microorganisms, including *E. coli*, are derived not only from human sources of faecal pollution, but also from wild and domestic animals, including birds (Kator & Rhodes 1991). Enteric viruses are also a major problem, and are not detected by the use of normal bacterial indicators. In addition, some marine bacteria (e.g. *Vibrio* sp.) can also cause illness in consumers. Thus, it is important that techniques to monitor these types of organisms are developed and implemented. Some states are currently investigating other indicators for enteric viruses (e.g. coliphage) (K Lee pers comm 2000).

The ASQAP categories of classification are based on levels of contamination from sewage, poisonous or deleterious substances, other pathogenic organisms of non-faecal origin and biotoxin-producing organisms, radionuclides, and toxic wastes. The criteria for each classification are contained in the ASQAP Operations Manual (ASSAC 1997). The classifications that can result from the analysis of sanitary surveys are as follows:

- **Approved:** Shellfish harvesting areas which as a result of a sanitary survey and marine biotoxin monitoring have been found not to contain faecal material, pathogenic organisms or toxic or deleterious substances in levels that may affect public health should be classified as approved. Shellfish harvested from harvesting areas classified as approved can be sold directly for human consumption (direct marketing).
- **Conditionally approved:** This classification has the same sanitary quality as the Approved classification for most of the time. However these area may be subject to intermittent pollution from events which may be a potential threat to public health (e.g. failure of waste water treatment plant, seasonal increase in the human population, high rainfall causing run-off of pollutants and seasonal anchorage of a fishing fleet). These intermittent pollution sources must be predictable to allow appropriate management plans to be developed. The development and monitoring of these management plans require substantial resources. Conditional approved areas are closed to harvesting when the coliform concentrations exceed the approved area classification standards.
- **Conditionally restricted:** This classification is the same as for the conditional approved classification, except that the area is closed when the coliform concentrations exceed the restricted area classification criteria but are open to harvesting for relaying or depuration when the coliform concentrations meet the restricted area classification bacteriological standard. As for conditionally approved area.

- **Restricted area:** A restricted area classification might be considered where the harvesting area does not meet the approved area classification criteria but is not grossly polluted. Shellfish may be harvested if subjected to a suitable, effective purification process before being sold for consumption (e.g. depuration or relaying). A common situation where this classification might be appropriate is for harvesting areas affected by non-point source pollution from either urban or rural sources which cause the water quality to fluctuate unpredictably or of sufficient frequency that a conditional approved area classification is not feasible.
- **Prohibited area:** These are areas that are not properly surveyed, and hence of undetermined quality, or which contain excessive contaminants (i.e. human sewage, industrial and agricultural chemicals) or toxic substances (i.e. toxic algal species). Harvesting of shellfish from these areas is prohibited.

Following classification, routine monitoring is implemented.

New Zealand

New Zealand is an active member of the Australian Shellfish Quality Assurance Program.

New Zealand operates a mandatory shellfish quality assurance program for all commercial bivalve shellfish areas. The New Zealand Shellfish Quality Assurance Program (NZSQAP) is overseen by the Ministry of Agriculture (MAF) Food Assurance Authority, but involves a partnership with the Ministry of Health. This program is based on the United States Food and Drug Administration program but has been further developed to manage conditions that are unique to the New Zealand environment and aquaculture industry.

The program requires that a full sanitary survey of each growing area catchment be undertaken on public health grounds to assess the risks of the growing waters being contaminated. Areas highly susceptible to microbiological (including viruses) or chemical contamination would not be approved for harvest. Shellfish growing waters can be classified as:

- **Approved** areas when, under the most unfavourable meteorological, hydrographic, seasonal or point-source conditions, the total coliform median or geometric mean MPN of the water does not exceed 70 per 100 mL and fewer than 10% of the samples exceed a five-tube MPN of 230 per 100 mL (or a three-tube MPN of 330 per 100 mL). In addition, faecal coliforms do not exceed 14 per 100 mL and fewer than 10% of samples exceed a five-tube MPN of 43 per 100 mL (or a three-tube MPN of 49 per 100 mL). At least 15 samples must be analysed. Failure to meet the standards results in temporary closure of the waters.
- **Remote approved** areas have no human habitation in the growing area catchment and not impacted by any actual or potential pollution sources. The area shall meet the approved area requirements specified above, except that the number of samples for adverse pollution condition sampling may be varied at the discretion of the authorised health officer.
- **Conditionally approved** areas when the waters are subject to bacterial contamination events, such as from heavy rainfall in the catchment or discharge of sewage. If such an event occurs the State Shellfish Control Agency (SSCA) will conduct a sanitary survey and either approve harvesting if sanitary standards (as above for Approved Waters) are maintained, or close the area until further surveys demonstrate that the sanitary standards have been attained again.
- **Restricted** areas when the waters are subject to limited amounts of pollution such that shellfish must be depurated or relayed prior to sale. Under the most unfavourable

meteorological, hydrographic, seasonal or point-source conditions, water samples should not have total coliform levels in excess of 700 per 100 mL with fewer than 10% of samples exceeding 2300 per 100 mL for a five-tube MPN. In addition, faecal coliforms must not exceed 88 per 100 mL, with fewer than 10% of samples exceeding 260 per 100 mL for a five-tube MPN, or 300 per 100 mL for a three-tube MPN.

- **Conditionally restricted** areas when the waters are subject to intermittent pollution which makes them temporarily unsuitable as a source of shellfish for depuration or relaying. The waters are closed for harvesting until they can meet the sanitary criteria for restricted waters.
- **Prohibited** areas when the level of pollution is such that shellfish are likely to be unfit for human consumption even after depuration or relaying. The harvesting of shellfish is banned from such waters.
- **Unclassified** areas when no sanitary survey has been conducted. Harvesting of shellfish from such areas is banned.

After the sanitary survey has been completed a routine water/flesh sampling program is implemented to monitor for microbiological, chemical and marine biotoxin contamination. If the water quality does not meet the minimum standards for microbiological, marine biotoxin or potential chemical parameters, harvesting from those areas effected is prohibited until monitoring shows that the standards are being met again.

Sampling, testing and monitoring of shellfish growing waters is at the expense of individual industries and is regulated by quality control centres which arrange regular testing and inspection of shellfish growing sites. The mandatory marine biotoxin program includes both phytoplankton and shellfish monitoring. The program is approved by the Marine Biotoxin Technical Committee and may be found in the National Marine Biotoxin Management Plan.

Further details on the program may be found in Industry Agreed Implementation Standard 005.1: Shellfish Quality Assurance Circular. A copy of this standard may be found on the following web address — www.maf.govt.nz/Standards/seafood/iais/5/005.pdf.

For further explanation contact Phil Busby, National Manager Seafood, MAF Food Assurance Authority, PO Box 2526, Wellington, New Zealand, tel: +644 474-4167, fax: +644 474-4239.

European Union

European shellfish growing area classification is based on faecal coliform levels in shellfish meat. Annual classifications of growing areas are performed by regulatory agencies in each country. The European Council Directive (1992) sets the standards for each of the four growing area classifications:

- *Class A* areas are approved for harvesting shellfish that can be sold directly to the public, with no purification required. Shellfish harvested from Class A areas must contain <300 faecal coliforms or <230 *E. coli* per 100 g of mollusc flesh and intravalvular fluid based on a five-tube three-dilution MPN test or other acceptable method. *Salmonella* must also be absent from 25 g of mollusc flesh. In addition, there must be no positive results for Diarrhetic Shellfish Toxin and the amount of Paralytic Shellfish Toxin must be <80 micrograms per 100 g of mollusc flesh. Radionuclide levels are also specified.
- *Class B* areas are approved for harvesting, but all shellfish must be purified (by relaying or depuration) or cooked by an approved method prior to sale to the public. Shellfish in

Class B areas must have <6000 faecal coliforms or <4600 *E. coli* per 100 g of mollusc flesh in 90% of samples.

- *Class C* areas are not approved for immediate harvesting. Instead shellfish from these areas must be relayed for a prolonged period (at least two months). This process may also be combined with purification to ensure shellfish meet microbiological end-product standards. Alternatively, shellfish may be harvested and cooked by an approved method prior to sale for human consumption. Shellfish from Class C areas must have <60 000 faecal coliforms per 100 g of mollusc flesh.
- *Class D* areas are those from which harvesting of shellfish is totally prohibited. Shellfish in these areas have >60 000 faecal coliforms per 100 g of mollusc flesh. In addition, areas may be designated as prohibited at the discretion of the state.

Any of the above classified areas may be subject to closure if routine monitoring indicates that sanitary standards are being exceeded. In addition, the EC Directive specifies criteria that must be met for all aspects of shellfish processing (e.g. the treatment of shellfish during harvesting, transport and storage). The level of continued monitoring required to maintain the growing area classifications, varies between countries.

USA and Canada

In the USA, the National Shellfish Sanitation Program (NSSP) of the Food and Drug Administration classifies waterways for shellfish harvesting on the basis of a sanitary survey of the growing area, in addition to an ongoing strategic water sampling program. A protocol for depuration has also been established (NSSP 1990 a,b, NSSP 1995 a,b). A similar classification system operates in Canada. The NSSP emphasises the importance of the sanitary survey in determining acceptable and unacceptable growing areas and requires that the survey of the waterway be updated annually. The NSSP also establishes contingency plans for marine biotoxins and other deleterious substances (e.g. pesticides and heavy metals). Shellfish growing waters are then annually classified as:

- **Approved** areas when, under the most unfavourable meteorological, hydrographic, seasonal or point-source conditions, the total coliform median or geometric mean MPN of the water does not exceed 70 per 100 mL and fewer than 10% of the samples exceed a five-tube MPN of 230 per 100 mL (or a three-tube MPN of 330 per 100 mL). In addition, faecal coliforms do not exceed 14 per 100 mL and fewer than 10% of samples exceed a five-tube MPN of 43 per 100 mL (or a three-tube MPN of 49 per 100 mL). At least 15 samples must be analysed. Failure to meet the standards results in temporary closure of the waters.
- **Conditionally approved** areas when the waters are subject to bacterial contamination events, such as from heavy rainfall in the catchment or discharge of sewage. If such an event occurs the State Shellfish Control Agency (SSCA) will conduct a sanitary survey and either approve harvesting if sanitary standards (as above for Approved Waters) are maintained, or close the area until further surveys demonstrate that the sanitary standards have been attained again.
- **Restricted** areas when the waters are subject to limited amounts of pollution such that shellfish must be depurated or relayed prior to sale. Under the most unfavourable meteorological, hydrographic, seasonal or point-source conditions, water samples should not have total coliform levels in excess of 700 per 100 mL with fewer than 10% of samples exceeding 2300 per 100 mL for a five-tube MPN. In addition, faecal coliforms must not exceed 88 per 100 mL, with fewer than 10% of samples exceeding 260 per 100 mL for a five-tube MPN, or 300 per 100 mL for a three-tube MPN.

- **Conditionally restricted** areas when the waters are subject to intermittent pollution which makes them temporarily unsuitable as a source of shellfish for depuration or relaying. The waters are closed for harvesting until they can meet the sanitary criteria for restricted waters.
- **Prohibited** areas when the level of pollution is such that shellfish are likely to be unfit for human consumption even after depuration or relaying. The harvesting of shellfish is banned from such waters.
- **Unclassified** areas when no sanitary survey has been conducted. Harvesting of shellfish from such areas is banned.

Shellfish harvested from approved or conditionally approved waterways that meet approved area criteria may be harvested and sold directly. Depuration or relay is required for shellfish harvested from conditionally approved areas not meeting approved criteria, and for shellfish harvested from restricted areas or from conditionally restricted areas that meet restricted area classification.

The practice of depuration in the USA is strictly controlled by the SSCA. A scheduled depuration process (SDA) is established for each depuration facility (NSSP 1995b). This process evaluates the effectiveness of the plant to reduce the number of microorganisms in shellfish harvested from restricted waters on the basis of experimental data. In addition the SDA assesses plant design and construction and process variables such as environmental parameters. This process of verification results in the determination of a maximum initial level of faecal coliforms for each plant. Each batch of shellfish to be depurated must be sampled from the harvest lot and also after the depuration process. All samples are analysed for the presence of faecal coliforms by the MPN method. Rigid sampling regimes specify the number of samples which are required from each batch and the number of samples is dependent on the number of areas harvested and the variability of pollution in each area. End-product standards have been established for each shellfish species commercially harvested. Shellfish are depurated for at least 48 hours.

3. Phytoplankton monitoring

Phytoplankton monitoring may prove useful as a predictor of marine biotoxins appearing in shellfish. However, phytoplankton monitoring is undertaken only in certain parts of Tasmania, South Australia and Western Australia as part of a routine marine biotoxin monitoring program. This shortcoming is being examined as part of the National Biotoxin Strategy Project, a FRDC funded project. Cost-effective tests to monitor for the presence of biotoxins are urgently needed, although monitoring is probably hindered by high costs and the current principal of cost recovery from industry (K Lee pers comm 2000).

New Zealand uses phytoplankton within the comprehensive marine biotoxin management program that is mandatory for all commercial harvest areas. A similar program is operated by the Ministry of Health for all recreational shellfish harvesting sites. A combination of phytoplankton and flesh tests are used to monitor for biotoxin activity. Commercial areas are sampled weekly for biotoxin activity and should mandated trigger levels be reached for a number of species, flesh testing is invoked immediately. The trigger levels are those listed in table 9.4.47.

Further specific details on the mandatory monitoring requirement and regulatory test methods may be obtained by contacting Phil Busby, National Manager Seafood, MAF Food Assurance Authority, PO Box 2526, Wellington, New Zealand, tel: +644 474-4167, fax: +644 474-4239.

Table 9.4.47 Levels of risk assessment with regard to phytoplankton cell numbers (MBMB 1996)

Species	Toxin *	Risk	Cell/litre
<i>Alexandrium</i> spp.	PSP	Low Moderate High Very high	1–200 201–1000 1001–5000 >5001
<i>Dinophysis acuminata</i>	DSP	Low Moderate High Very high	1–1000 1001–2000 2001–10 000 >10 001
<i>Dinophysis acuta</i>	DSP	Low Moderate High Very high	1–500 501–1000 1001–5000 >5001
<i>Gymnodinium</i> sp.	NSP	Low Moderate High Very high	1–1000 1001–2000 2001–10 000 >10 001
<i>Prorocentrum lima</i>	DSP	Low Moderate High Very high	1–500 501–1000 1001–5000 >5001
<i>Pseudonitzschia</i> sp.	ASP	Low Moderate High Very high	1–50 000 50 001–200 000 200 001–500 000 >500 001
<i>Rhizosolenia</i> sp.	<i>can cause bad taste & shellfish deaths</i>	Low Moderate High Very high	1–50 000 50 001–200 000 200 001–500 000 >500 001

* ASP = Amnesic shellfish poisoning, DSP = Diarrhetic shellfish poisoning, PSP = Paralytic shellfish poisoning

In New Zealand, the shellfish industry have requested that they be notified where levels of certain phytoplankton species (table 9.4.48) are exceeded so that harvesting decision can be made.

Table 9.4.48 Notification levels for phytoplankton cell numbers (MBMB 1996)

Species	Cell/litre
<i>Alexandrium</i> sp.	200
<i>Dinophysis</i> spp.	500
<i>Gymnodinium</i> cf. <i>breve</i>	1000
<i>Prorocentrum lima</i>	500
<i>Pseudonitzschia</i> sp.	100 000 (below 50% of total phytoplankton)
<i>Pseudonitzschia</i> spp.	50 000 (below 50% of total phytoplankton)

4. Three-phased screening approach

This is recommended by Zweig et al. (1999) and utilises expert water quality analysis laboratories to do the assay for the water quality. It is designed for aquaculture operations to evaluate source water quality in a step-by-step process to minimise costs to the degree possible.

For Phase I the water quality criteria of the source water for the basic physio-chemical properties necessary to sustain the cultured organisms are measured. This provides a simple means of screening the source water without going through the more expensive tests for the

chemical or natural contaminants. Zweig et al. (1999) suggest that if chemical or natural contaminants are not suspected, and Phase I criteria are met, then the source water can be considered acceptable. If the Phase I criteria are not met, there are three options:

- water source is rejected (look for another site);
- undertake a Phase III field trial; or
- assess the technical and economic feasibility of treating the source water to bring it within acceptable Phase I criteria.

Phase II is designed to screen criteria on anthropogenic (of human origin) pollutants and biological contaminants. 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 catchment should be tested. If the Phase II criteria are not met, the feasibility of pre-treating the source water 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, Zweig et al. (1999) advise that Phase III be pursued, if possible, as a means of minimising the risk of project failure.

Phase III involves a pilot study or field test in which the culture species are grown in the selected source water, using similar management techniques as those of the proposed project. They would then be tested for bioaccumulated pollutants and off-flavour. The pilot study could also be replaced by sampling cultured animals from an existing aquaculture facility, if available, which is using the same source water and the planned technology.

Following Phase III where implemented, a final decision can be made on the use of the source water.

9.4.4 Some precautionary comments

These guidelines have been developed on the basis of information currently available (to the middle of 1996; see comments in Section 9.4.5 and 4.4.7 regarding future work) for Australian and New Zealand aquaculture species. The approach (detailed in Section 9.4.1.4) was to concentrate the information search on one or two representative species from each of eight species groups, or categories. While the focus of the search allowed data on the commonly cultured species to be collated, it soon became apparent that despite increases in aquatic toxicology research in Australia and New Zealand in the past ten years, no information is available for some important aquaculture species. This is particularly the case for non finfish species. Section 9.4.5 details many of the deficiencies and makes suggestions for future research needs.

A review of the data presented in Section 9.4.2 shows that the toxicological data are occasionally contradictory. When carefully viewing the data it becomes apparent that the toxicity values sometimes differ by several orders of magnitude, i.e. one source may recommend a value of 1 mg/L for a toxicant, whereas another lists 0.01 mg/L for the same toxicant. This is highly confusing to the reader and certainly makes the guidelines appear less credible. Differences in data for given species were most likely due to different methods of exposure — i.e. time and duration of exposure, size and age of fish, and test conditions: temperature, pH etc.

However, the stringency of the various researchers' methods is unknown, thus when using the guidelines the following should be considered:

- More recent data may be more reliable than data previously published due to improved technology and methods.
- In cases where differences in acceptable/tolerated concentrations are extreme between different researchers, it is suggested to use the general guideline and proceed with caution, i.e. monitor fish for signs of avoidance behaviour, stress, etc.
- In the case of organic toxicants, these compounds are extremely persistent in the environment and thus have the potential to accumulate in the sediments. This is particularly important for bottom feeders, so sediments should also be monitored for levels of these compounds. Additionally, other adverse effects such as stress and immunosuppression can occur at levels much lower than those causing clinical toxicity.

Additionally, much of the data are traced from other databases or compilations, i.e. from secondary sources. Thus, much of the original literature is not based on recent research, but dates back more than ten or twenty years. Analytical methods applied at that time may not have been as sophisticated as they are today, and this may be one reason that the guidelines sometimes differ by several orders of magnitude: for example, the lowest level detectable for a toxicant 'x' twenty years ago may have been 1 mg/L. Toxic effects may have been observed at any level above this detection limit. Where toxicity was occurring below the detection limit, either it would not have been picked up or it was attributed to background. Necessarily, the *safe* level would therefore have been determined as <1 mg/L. Today, refined analysis may be able to show that, in fact, even at 0.1 mg/L a toxic effect can occur, and thus the *safe* level has to be refined.

The definition of toxicity itself is not straightforward, nor is the set-up of toxicity tests consistent, so there will always be dispute about the applicability of published values and derived guidelines. A number of other drawbacks to this approach can be identified:

- 1 In aquaculture, the culture species are in an artificial farm environment where: avoidance of pollutants is impossible due to physical constraints of the culture structures; the feed is usually not derived from the immediate environment (except in the case of bivalves and some freshwater fish and crayfish) so oral exposure to pollutants is unrelated to ambient concentrations; and there are additional stresses due to farming procedures (e.g. any procedure requiring handling, higher stocking densities).
- 2 Aquatic toxicological studies often involve the use of surrogate species of no commercial value. While this information cannot be extrapolated easily to aquaculture species under farming conditions, it can be a good starting point for future considerations.
- 3 Tolerance to individual pollutants is very variable between species, even within the species groups selected in table 9.4.1. For example, Davies et al. (1994) noted that safe levels of contamination for several types of pesticides calculated from *Oncorhynchus mykiss* toxicity data were not suitable for the protection of juvenile and adult *Galaxias maculatus* and *Pseudaphritis urvilli* from physiological stress in at least three of seven cases of exposure.
- 4 Many chemicals break down into a number of isomers and metabolites. Some forms of a chemical compound or an element are more biologically available and, thus, often more toxic. For example, metal speciation (Section 3.4.3) is very important but rarely reported,

with free ions usually being more toxic. For this reason a multidisciplinary research approach, combining toxicology and chemistry is required.

- 5 The physiological effect of a substance (e.g. on reproductive potential and growth) may be just as important as the direct toxicity of the substance. Unfortunately, most studies only include data on direct toxicity.
- 6 In aquaculture it is desirable to maintain the concentration of a potential toxicant below the level that is known to have any adverse effect on the culture species. Yet, the toxicity of most substances is proportional to the time of exposure. The toxicity tests are usually undertaken over a short period (24 hr to 96 hr) and undesirable sublethal effects of a substance may not be revealed. For aquaculture, chronic long-term effects are important. For example, fish may tolerate 3 mg/L DO₂ for several days without apparent harm, but over a longer period the fish growth could be lowered and the fish could become more susceptible to diseases. Not only would mortality affect farm production but also reduced food conversion ratio (FCR), reduced growth, and increased sensitivity to pathogens could occur. Unfortunately, chronic long-term data are not available for most toxicants and aquaculture species.
- 7 Toxicity data are reported as nominal or measured values; nominal values are less accurate than measured ones and can result in an underestimation of toxicity due to unknown loss of toxicant during the test.
- 8 Toxicity data are based on static, semi-static or flow-through tests: flow-through tests tend to give the lower toxicity values since the toxicant is always present in the experimental system at a constant level. Toxicant levels in static or semi-static tests may decrease during the whole test (static tests) or until renewal (in semi-static tests). Unless exposure to the toxicant in the environment is pulse rather than constant, it would be more appropriate to use flow-through test results.
- 9 Toxicity of chemicals is related to the physiological state of fish or other aquatic organisms affected by water quality, most importantly temperature, but also other variables such as water hardness and pH. Fish metabolic rate may double for every 10°C rise in temperature, resulting in increased uptake of toxicants. Additionally, temperature or low oxygen related stress could increase susceptibility to toxic effects.
- 10 Due to logistics, toxicity tests often use small size animals or early life stages. Toxicity, however, may change with life stage (often larvae are most sensitive) and size (usually smaller fish are affected earlier). This is because the weight-specific metabolic rate of fish decreases in larger fish and, thus, they may take up toxicants more slowly than smaller fish.
- 11 The source of test animals (wild population or cultured specimens) and the environment in which the animals lived previously may affect results of toxicity tests and, as a consequence, lead to overestimation or underestimation of toxicity of the tested compound.
- 12 Aquaculture animals may sometimes be exposed to a mixture of toxicants or other water quality parameters at suboptimal levels. For example in Macquarie Harbour, Tasmania, fish may be exposed to increased copper levels in association with low pH and low salinity. The results of standard toxicity tests provide little information about potential synergistic and antagonistic effects of combinations of pollutants.

- 13 Although no observed effects concentrations (NOECs) have been used to determine many of the water quality guidelines in this document, there is some opposition to their use in the scientific community because they are not a valid statistical endpoint.
- 14 For much of the data presented in the tables, no information is given on the type of endpoint measured in the test. If the result of the test is expressed as LC_{50} , the result will be much greater than NOEC values.

9.4.5 Priorities for research and development

Although there has been an increase in research in aquatic toxicology in Australia and New Zealand, information is still lacking on the effects of toxicants and water quality parameters on Australian and New Zealand aquaculture species, particularly invertebrates and marine/brackish water finfish. The majority of information utilised in this report concerned freshwater finfish species. However, not many data are presented for the species that contribute the majority of aquaculture production in Australia and New Zealand. This is of concern because those particular marine and coastal enterprises have to exist in waters that are likely to be impacted by other activities and they would be well-advised to monitor their water quality closely.

The other most obvious deficiency is the absence of guidelines for juvenile life forms. This is unfortunate, as in most cases the juvenile forms will be more susceptible. Thus, while the guidelines provided may be of use to grow-out aquaculture enterprises, they are of little use to hatcheries or closed-cycle operations. However, this potential shortcoming is also evident in other major reviews, including CCME (1993), Svobodova et al. (1993), DWA (1996), and Zweig et al. (1999).

Deficiencies in the data did not allow a critical or statistical analysis of the data to be made before deriving the water quality guidelines in Sections 9.4.2 and 9.4.3. With the rapidly increasing aquaculture industry in Australia and New Zealand, there is an urgent need to determine water quality guidelines with higher confidence levels. Whilst some new information has become available (particularly Zweig et al. 1999) and has been incorporated into the current report, the search of appropriate literature and databases was originally completed in June, 1996. Thus, the data can be considered incomplete.

The priority for future work (R&D) should be the collation of all available water quality toxicity data relevant to Australian and New Zealand aquaculture species (both adult and juvenile life forms) onto a database so that guidelines can be developed from a critical analysis of the data. Where appropriate, overseas data for the same species can also be incorporated into the database. It would then be possible to identify the species and compounds for which there are significant gaps in toxicity data.

Further research should concentrate on developing data for juvenile forms of important aquatic species, and for aquatic invertebrates, marine finfish and brackish water finfish. In the case of species logistically difficult to test (e.g. southern bluefin tuna) surrogate species should be evaluated or the use of *in vitro* tests and modelling further investigated.

A specific area of research may be to explore the use of bio-indicator species, be they animals or plants. With funds becoming ever more restricted, it is foreseeable that expensive analytical apparatus will not be widely available, and cheaper methods will be necessary. As well as reduced costs, another advantage of using bio-indicators is that they may be sensitive to a wide range of toxicants, indicating a more general unsuitability of the water for culture. While this approach may sound unacceptable to the analytical scientist, from a farmer's point

of view it seems to be the more sensible approach for on-going monitoring. After all, the farmer is not desperately concerned about the exact ppm level of any one particular agent, but needs to know whether his/her aquatic animals will thrive.

The experiments should be long term, and non-lethal effects such as health, reproduction and growth should be investigated. Issues around bioaccumulation and assimilation also need to be addressed, as do the movement of contaminants or toxicants out of disturbed sediments and into the water column.

Interactions between toxicants and deteriorating or changing water quality should be determined. The effects of mixtures of toxicants should also be investigated. These studies should be undertaken under realistic environmental conditions (i.e. tested concentrations should reflect environmental pollution, in order to realise true farming situations).

Multidisciplinary studies investigating toxicity, chemistry and biology should be undertaken. Long-term monitoring studies on farms should be encouraged to define environmental conditions affecting production. There is need for a computer database combining toxicity data (from both Australia and overseas) with environmental data from culture areas and results of case studies from Australian aquaculture. Responsible agencies/organisations for the establishment and maintenance of this database is yet to be determined.

More research is needed to determine the effects of chemical speciation and different isomers on toxicity of an element or compound. All experiments and monitoring should be properly designed to allow for statistical evaluation of the results.

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