GRAND RIVER BASIN

WATER MANAGEMENT STUDY

TECHNICAL REPORT SERIES

WATER QUALITY REQUIREMENTS FOR SPORT FISHES IN THE GRAND RIVER WATERSHED

A LITERATURE REVIEW

TECHNICAL REPORT No. 13

Ontario

GRAND RIVER IMPLEMENTATION COMMITTEE

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A LITERATURE REVIEW

PREPARED FOR :

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FOREWORD

The report "Water Quality Requirements for Sport Fishes of the Grand River Watershed: A Literature Review" is one of a series of technical documents prepared for the Grand River Basin Water Management Study Team under the authorization of the Grand River Implementation Committee.

The information contained in this report is intended to provide guidance in assessing the impact of a wide range of water quality parameters for those types of sport fishes found in the Grand River Basin. The report in itself does not constitute policy or management practices. Questions with respect to the contents of this report should be directed to the Co-ordinator of the Grand River Study, c/o J. G. Ralston, Water Resources Branch, Ministry of the Environment, 135 St. Clair Avenue West, Toronto.

ACKNOWLEDGEMENTS

The writers wish to express their appreciation to all of the technical specialists who reviewed this report. Although too lengthy to list here, their names and affiliations are contained in Appendix I.

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INTRODUCTION

In the spring of 1978, the Grand River Implementation Committee (GRIC) commissioned the Ontario Ministry of Natural Resources, Cambridge, to review current literature on water quality requirements of major sport fishes inhabiting the Grand River Watershed. This resulting report can in no way claim to be a complete review of the extensive and rapidly expanding toxicological literature. In spite of this limitation, we feel that this report will serve as one of several valuable guidelines in assessing water quality requirements for sport fishes in the Grand River Watershed.

In water quality documents, three terms appear repeatedly (IJC 1977) and are mistakenly used interchangeably. Criteria are maximum levels of toxicants or other substances that can be considered safe for a particular use over extended periods of time. They are based strictly on scientific evidence, and are usually proposed by a group of scientists brought together for the purpose by some agency. Objectives are goals set by an agency for levels of various toxicants or other conditions. They may reflect not only established criteria, but also the ability to detect or measure parameters and historical background levels of the substance in question. Standards are criteria or objectives that have been included in the laws of a government and which are enforceable.

Water quality criteria proposed by one group may not be accepted by others. The acceptance of, or modifications to water quality criteria in specific situations may take into account local conditions such as natural background levels, presence/absence of important sensitive species, and antagonistic or synergistic effects of combinations of pollutants. In this report, established criteria and objectives are presented along with documented effects on fish of certain levels of pollutants under prescribed conditions.

Although these data certainly provide useful reference points for identifying conditions necessary to protect fish, it must be emphasized that because of the wide variety of physical and chemical characteristics existing in stream systems, it is not the intent of this report to define conditions that will ensure the maintenance of healthy fish populations for any given watershed. The prime purpose of this review is to provide the best possible information concerning water quality impacts on and requirements for sport fishes under well defined conditions. As these well defined conditions rarely apply consistently to fishes in the Grand

River Basin, or any given natural watercourse, the data documented herein can only provide a guide to favourable conditions or conditions to be avoided.

It should be pointed out that during the preparation of this report, the Ministry of the Environment published "Water Management - Goals, Policies, Objectives and Implementation Procedures of the Ministry of the Environment, November, 1978. That document, often referred to as the Blue Book contains provincial water quality objectives in support of the MOE's surface water quality goal - "to ensure that the surface waters of the Province of Ontario are of a quality which is satisfactory for aquatic life and recreation". In a companion publication "Rationale for the Establishment of Ontario's Provincial Water Quality Objectives, September, 1979", the scientific reasons for the selection of the objectives are compiled. Although MOE objectives are cited throughout this document, readers are advised to review the MOE publications.

APPROACH

This literature review, in general focuses on three sport fishes which occur in the Grand River Watershed, and which tolerate different water quality; rock bass, smallmouth bass and brook trout. Unfortunately information on rock bass is sparse, so data on two less common Centratchids (largemouth bass and bluegill) in the watershed are included. Information on other fresh water fish species is included in certain areas to broaden the perspective.

Sprague (1971) reviewed sublethal effects of pollutants and the rationale for deciding safe levels for fish. He discussed the advantages and disadvantages of studying various fish responses during bioassay experiments; these are given below:

1. Growth - easy parameter to measure, but is not always a sensitive indicator of toxicity.

2 Swimming speed - less often affected by toxicants than might be expected; clear cut effects are usually related to impaired respiration. A toxicant might be assessed by testing whether it reduced the fishes scope for activity (active minus standard oxygen uptake).

3. Behavioural change - often a very sensitive response, although its significance in nature may be uncertain. Avoidance reactions to many pollutants have been demonstrated in the laboratory, but no pattern of predicting avoidance in nature is yet available. Effects of toxicants on social interactions should be explored.

4. Feeding behaviour - adversely affected by some pollutants.

5. Histopathological and biochemical techniques - these have demonstrated sublethal changes within fish.

6. Reproduction - seems to be one of the most sensitive, chronic or sublethal responses which is clearly meaningful in nature. It is sometimes sharply affected through inhibition of spawning or through toxicity to fish fry.

In the following pages, many bioassay results are quoted. The above mentioned factors should be taken into consideration when interpreting these results, and discussing water quality criteria. For each physical or chemical variable the concentration found to be safe, sublethal, and lethal to fish held under well defined conditions are cited. However, the information on the effects of some physical or chemical variables on fish species is limited.

1. DISSOLVED OXYGEN

1.1 Criteria

Reports by Davis (1975a, 1975b) and Duodoroff and Shumway (1970) are the most comprehensive works to date on dissolved oxygen requirements of freshwater fishes. These studies have been the basis for many of the criteria recommended by various agencies. Davis (1975b) established three levels of protection as defined below:

Level A - represents more or less ideal conditions (i.e. little or no foreseeable harm) and permits little depression of oxygen from full saturation. It represents a level that assures a high degree of safety for very important stocks in prime areas.

Level B - some degree of risk (i.e. possibility of moderate harm) to a portion of a fish population exists if the oxygen minimum period is prolonged beyond a few hours.

Level C - a large portion of a given fish population or fish community may be affected by low oxygen. Deleterious effects may be severe (i.e. possibility of severe harm), especially if the oxygen minimum is prolonged beyond a very few hours.

Utilizing these levels of protection, minimal oxygen concentrations for Canadian freshwater fish, range from 3.0 to 5.1 mg/L (Level C) for non-salmonids and from 8.4 to 14.3 mg/L for salmonid larvae and eggs (Level A) at temperatures of 0 to 25°C (Table 1.1).

MOE (1978) states that at no time should dissolved oxygen concentrations be less than the values specified below:

Table 1.1 Minimal oxygen criteria for various assemblages of Canadian freshwater fish (from Davis 1975b).

Water Temperature (°C)		Populations with no salmonids			Populations with some salmonids			Populations with mainly salmonids			Salmonid larvae and mature salmonid eggs		
		A	B	C	A	B	C	A	B	C	A	B	C
0	% sat.	60	47	35	69	54	38	76	57	38	98	76	54
	mg/L	8.8	6.9	5.1	10.1	7.9	5.6	11.1	8.3	5.6	14.3	11.1	7.9
5	% sat.	60	47	35	70	54	38	76	57	38	98	76	54
	mg/L	7.7	6.0	4.5	9.0	6.9	4.9	9.7	7.3	4.9	12.5	9.7	6.9
10	% sat.	60	47	35	70	54	38	76	57	38	98	76	57
	mg/L	6.8	5.3	4.0	7.9	6.1	4.3	8.6	6.5	4.3	11.1	8.6	6.5
15	% sat.	60	47	35	71	54	38	76	59	42	98	79	64
	mg/L	6.1	4.8	3.6	7.2	5.5	3.9	7.7	6.0	4.3	9.9	8.0	6.5
20	% sat.	60	47	35	79	57	39	85	65	46	100	87	71
	mg/L	5.5	4.3	3.2	7.2	5.2	3.6	7.8	6.0	4.2	9.2	8.0	6.5
25	% sat.	66	48	36	87	63	39	93	72	51	100	95	78
	mg/L	5.5	4.0	3.0	7.3	5.3	3.3	7.8	6.0	4.3	8.4	8.0	6.5

Level of protection or risk commitment

A - represents near ideal conditions (i.e. little or no foreseeable harm)

B - some degree of risk (possibly moderate harm if oxygen minimum prolonged beyond a few hours.

C - high risk (possibly large proportion of fish may be affected if oxygen minimum is prolonged beyond a few hours.

mg/L - concentrations calculated for atmosphere containing 20.9% oxygen under a pressure of 760mm Hg (including pressure of water vapor).

DISSOLVED OXYGEN CONCENTRATION

Temperature	Cold Water Fish		Warm Water Fish	
°C	% Saturation	mg/L	% Saturation	mg/L
0	54	8	47	7
5	54	7	47	6
10	54	6	47	5
15	54	6	47	5
20	57	5	47	4
25	63	5	48	4

It is emphasized that in situations where additional physical and/or chemical stresses are present, that these minimum levels may prove inadequate and more stringent objectives may be necessary. Several other reports suggest minimum dissolved oxygen concentrations for the protection of aquatic life. Petit (1973) recommends a minimal value of 6.0 mg/L for non-salmonids at 15 and 22°C. To maintain good fish populations EPA (1976) recommends a minimal value of 5.0 mg/L in the water column and in interstitial water of the gravel of salmonid spawning beds. The Aquatic Life Advisory Committee (1955) also suggested that a minimal value of 5.0 mg/L should exist for at least 16 hours per day and never be less than 3.0 mg/L for warm water species.

Dissolved oxygen criteria are generally based on the long term average oxygen concentrations that fish require. However, it is also important to consider the oxygen concentrations that fish can tolerate for short periods. Doudoroff and Shumway (1970) believe that oxygen concentrations down to 3 mg/L for less than 1 to 2 days are not likely to kill fully developed fish provided no other stresses are present and also that cyclic diurnal oxygen super-saturation would not be lethal. This last statement is further supported by Wiebe (1933) who found that several fish species tolerated sudden changes (time period not stated) in oxygen concentration in either direction (i.e. from 5.67 - 40.33 mg/L and 41.2 - 7.3 mg/L). However, constant exposure to oxygen super-saturation may be lethal (Table 1.2a rainbow trout).

1.2 Responses of Individual Fish Species

In the previous sub-section (1.1) general dissolved oxygen criteria for most Canadian freshwater fish species were presented. These criteria were developed from syntheses of studies, usually on individual species. Although very useful because of their widespread applicability, in certain situations species-specific details of responses to dissolved oxygen concentrations may be desirable. The following tables present responses for brook, brown and rainbow trout, smallmouth and largemouth bass, and northern pike. For species with large data bases, only relatively few responses, covering the normal range of dissolved oxygen values, are presented.

Table 1.2a. Responses of brook trout to various dissolved oxygen concentrations.

O_2 mg/L	Temp. (°C)	Fish Response	Reference
7.6	15	Normal activity	Fry (1951)
from 11.0 to 5.3 and 3.5		Diurnal fluctuations - depressed growth of yearlings	Whitworth (1968)
from 11.0 to 2.0		Diurnal fluctuations - most yearlings were unable to tolerate	
9.1	20	Onset of O_2 - dependent metabolism	Graham (1949)
8.1	5	Onset of O_2 - dependent metabolism	Graham (1949)
6.0	8	Reduced cruising speed	Graham (1949)
5.2 to 5.7	10, 15	Standard O_2 uptake reduced below this level	Beamish(1964)
4.6	20	Blood not fully saturated with O_2 below this level	Irving *et al.* (1949)
2.0 to 3.4	12 - 21	Death may occur, loss of equilibrium	Burdick *et al* (1949)
2.0 to 2.5 (20% Saturation)		Marked effect on development and poor survival of embryos and larvae	Seifert & Spoor (1973)
1.9	9 - 10	Known to survive for short periods	Sheppard (1958)
1.0 to 1.8*	9	Lethal at constant concentration for 3.5d	Sheppard (1958)

* estimated incipient lethal level for varying acclimation oxygen levels.

Table 1.2b. Responses of rainbow trout and brown trout to various dissolved oxygen concentrations.

O_2 mg/L	Temp.(°C)	Fish Response	Reference
Rainbow Trout			
28 - 30	1.4	Constant exposure - death(yearlings) and altered behaviour of 2 yr. olds	Streltsova (1964)
20 - 25	13 - 15	Constant exposure - death	McCombie & Berst (1975)
24	1.4	Yearling behaviour - altered	Streltsova (1964)
from 9 - 11 to 7 - 8	10	Juvenile growth dropped significantly	Mekhanik (1957)
<6.7 - 8.7	2 - 13	Blood not fully saturated with oxygen	Itazawa (1970)
5.7 - 5.9	8 - 10	43% reduction in maximum swimming speed	Jones (1971)
<4.7 - 5.7	10 - 20	Blood not fully saturated with oxygen	Cameron (1971)
5.1	15	Respiratory quotient altered	Kutty (1968)
4.3 - 4.5	21 - 23	30% reduction in maximum swimming speed	Jones (1971)
3.0 - 4.0		Juvenile growth rate reduced by half	Mekhanik (1957)
2.5	>20	Lethal especially to juveniles	Ayles & Lark (1975)
<1.0	in winter	Adult and subadults survived over winter	McCombie & Berst (1975)
Brown Trout			
<4.6	20	Blood ceases to be fully saturated with O_2	Irving *et al.* (1949)
1.8	16	Minimum tolerable level for juveniles	Bishai (1960a)

Table 1.2c. Responses of largemouth and smallmouth bass to various dissolved oxygen concentrations.

O_2 mg/L	Temp. (°C)	Fish Response	Reference
Largemouth Bass			
20.0	26	Depressed juvenile growth	Stewart *et al.* (1967)
6.0	20 - 23	Larval growth reduced	Carlson & Siefert (1974)
< 6.0	22	Increased rate and amplitude of opercular movements	Petit (1973)
< 5.0 - 6.0	25	Juvenile maximum swimming speed reduced	Dahlberg *et al.* (1968)
			Katz *et al.* (1959)
< 4.1 - 5.0	20 - 23	Hatching premature and first feeding delayed	Carlson & Siefert (1974)
4.5		Some degree of avoidance	Whitmore *et al.* (1960)
4.0	20	Production reduced by 20% below that of saturation level.	Warren *et al.* (1973)
<4.0	26	Gross food conversion efficiency reduced	Stewart *et al.* (1967)
2.8	25	Increased embryo mortality	Dudley & Eipper (1975)
1.5		Strong avoidance	Whitmore *et al.* (1960)
1.3	25	Minimum level for any embryonic development and hatch	Dudley & Eipper (1975)
1.0		Bass fry survived "short term" sags to this level in mid-summer	Kramer & Smith (1962)
1.0		Bass survived through winter	Johnson (1965)
0.8	25	Minimum level survived	Moss & Scott (1961)
Smallmouth Bass			
> 3.0		Safe level (from mortality) for swimming juveniles	Eipper (1975)
1.3	27	Lethal to juveniles	Burdick *et al.* (1949)

Table 1.2d. Responses of northern pike and walleye to various dissolved oxygen concentrations.

O_2 mg/L	Temp. (°C)	Fish Response	Reference
Northern Pike			
< 6.0	22	Increased rate and amplitude of opercular movements	Petit (1973)
4.6 - 5.1	15 -19	Sufficient for development and survival through onset of exogenous feeding	Siefert *et al.* (1973)
3.0- 4.0	18.7	Reduced juvenile growth	Adelman & Smith (1970)
2.5 -3.1	15 - 19	Onset of exogenous feeding delayed 3 days; most died12h after beginning to feed	Siefert *et al.* (1973)
< 2.8	18.6	Marked decrease in food consumption, conversion efficiency and growth rate	Adelman & Smith (1970)
1.3	15	None survived to onset of exogenous feeding	Siefert *et al.* (1973)
0.8	21.4	Lethal	Casselman (1978)
0.3	(winter)	Survived over winter	Casselman (1978)
Walleye			
6.0	22	Increased rate and amplitude of opercular movements	Petit (1973)
3.9 - 4.6		Decreased survival, embryos and larvae	Siefert & Spoor (1973)
1.0 - 1.5	22	Juveniles abandoned light avoidance response	Scherer (1971)
0.6	22	Juveniles lost equilibrium and coordination	Scherer (1971)

2. WATER TEMPERATURE

2.1 Introduction

Fish are "cold-blooded" or poikilothermous animals with their internal body temperature usually approximating the ambient water temperature. As a result their survival, growth, distribution, and reproduction are directly affected by water temperature. Man alters natural temperature regimes of water bodies, most notably through impoundments, deforestation, discharges of waste heat, and channelization. Significant temperature changes over extended time periods may affect the structure of fish communities. Effects of temperature on individual fish species have long been studied and often reviewed (NAS/NAE 1973). Researchers often employ specific terminology, some of which is briefly explained below.

acclimation - the process of adjusting to a temperature change (through internal biochemical changes) usually requiring several days.

lethal threshold - the temperature at which a prescribed percentage of the test fish, acclimated to a specific temperature, will die during a specified time interval.(same as incipient lethal temperature).

optimum temperature - the temperature at which growth or some other physiological maxima occurs, it often approximates the final preferendum. (see preferred temperature).

preferred temperature - for each acclimation, the temperature most frequently selected by a fish in a thermal gradient. When the preferred temperature equals the acclimation temperature, it is known as the final preferendum. However, in common usage the term preferred temperature implies the final preferendum.

safety-factor- an amount by which upper lethal threshold temperatures, based on 50% mortality are reduced so that mortality becomes negligible, 2°C is most often used. (But see Thurston *et al.* 1979).

ultimate incipient lethal temperature - the threshold temperature beyond which a fish cannot be acclimated and will ultimately die with continued exposure.

zone of tolerance - the range of temperatures that a fish can withstand for a prolonged period of time; usually bounded by the lethal thresholds.

Time is always an important consideration when assessing both chronic and acute effects of temperature.

2.2 Criteria

Species - specific temperature criteria must be viewed in the context of annual cycles and the seasonal requirements of the various life history stages of the fish (Coutant 1975). That is, thermal requirements must be assessed for the most sensitive species in the group being considered, at the most sensitive stage of its life history (usually spawning and incubation) in the area inhabited by the fish. Therefore, separate thermal criteria are necessary for the growth, reproductive, and winter seasons for each species. In addition, these criteria can be sub-divided into prolonged and short-term exposures.

A. Growth Season

(i) Prolonged Exposure

To maintain growth at levels sustaining actively growing populations of fish, NAS/NAE (1973) devised the "Maximum Weekly Average Temperature" (MWAT):

$$MWAT = T_o + (T_u - T_o)/3$$

Where T_o is the optimum temperature (preferably for growth) and T_u is the ultimate upper incipient lethal temperature of the species. MWATs calculated by IJC (1978) are presented in Table 2.2 for some sport fishes. Temperature fluctuations above the weekly average must not exceed the criteria for short-term exposures.

(ii) Short-term exposures

The length of time fish can withstand a particular temperature, depends on the extent this temperature exceeds the lethal threshold (i.e. higher temperatures can be endured for relatively shorter periods). IJC (1978) calculations of maximum temperatures for survival for a 24 hour short-term exposure, assuming an acclimation temperature near the MWAT during the growth season, are provided for selected species in Table 2.2 (these calculations include the 2°C safety factor). For determinations at other acclimation temperatures and/or for other exposure times, consult IJC (1978) and data in Water Quality Criteria 1972 (NAS/NAE 1973). These criteria for maximum short-term exposures are to protect fish from lethal effects only.

B. Reproductive Season

Spawning and development are generally the most thermally sensitive stages in the life history of fish and criteria during these periods and where reproduction occurs, should supercede all others (NAS/NAE 1973).

i) Prolonged Exposures

During the reproductive season uniform elevations of temperature, while retaining natural cycles, may shift the timing of events (spawning, hatching) to earlier dates for spring spawners and later dates for fall spawners. These temperature increases may be acceptable provided they do not disrupt the synchrony of associated events such as food cycles and migrations (NAS/NAE 1973).

Table 2.2. Recommended (IJC 1978) maximum weekly average temperature (MWAT) and maximum temperature for 24 h short-term exposures, during growth and reproductive seasons of juvenile and adult sport fishes.

Species	Growth Season MWAT (°C)	Growth Season Max. for 24 h Short-term (°C)	Reproductive Season MWAT (°C)	Reproductive Season Max. for 24 h Short-term (°C)
Brook Trout	19	24	9	13
Brown Trout	17	24	8	15
Rainbow Trout	19	24	9	13
Northern Pike	28	30	11	19
Largemouth Bass	32	34	21	27
Smallmouth Bass	29	--	17	23
Walleye	25	--	8	17

IJC (1978) recommends the MWAT for spawning, as the optimum temperature for spawning if data are available, otherwise the middle of the range of spawning temperatures. Their determinations for selected species appear in Table 2.2.

(ii) Short-term Exposures

To protect developing embryos, and the completion of spawning itself, IJC (1978) recommends as criteria for short-term maximum temperature the maximum incubation temperature for successful embryo survival, or alternatively the maximum temperature for spawning. These criteria are listed in Table 2.2 for selected species.

C. Winter Season

(i) Prolonged Exposures

In winter, fish in the vicinity of heated discharges into the water body (i.e. from hydro-electric generating stations) become acclimated to these elevated temperatures. A shut-down of the discharge results in local water temperatures rapidly dropping to ambient levels. This temperature decline could prove lethal to some fish depending on the species, time period, and temperatures involved. Since data required for species-specific criteria are lacking, IJC (1978) proposes a general approach to the problem. From their calculations permissible maximum temperatures in the plume, or heated temperatures in the plume, or heated discharge, in areas inhabited by fish, are as follows.

Ambient Temp.(°C) (outside heated area)	Permissible Plume Temperature (°C) warm-water fish	cold-water fish
0	10	5
2.5	10	7.5
5	15	15
10	25	25

(ii) Short-term Exposures

These could be calculated using formulae and data supplied in IJC (1978) and Water Quality Criteria 1972 (NAS/NAE 1973) as for the growth season. However, data is limited for low acclimation temperatures.

2.3 Responses of Individual Fish Species

The following tables list documented effects of certain temperatures on selected fish species. These tables are not comprehensive and are provided only as an indication of potential effects of temperature alterations.

Table 2.3a. Responses of brook trout to various temperatures.

Temp. (°C)	Fish Response	Reference
25.5	Ultimate upper incipient lethal temperature	Fry *et al.* (1946)
21.0	Spermatozoa inhibited	Hokanson *et al.* (1973)
19.0	Maximum temperature for occurrence of natural breeding populations.	Hokanson *et al.* (1973)
16.0 - 19.0	Maximum temperature for normal maturation and ovulation in females.	Hokanson *et al.* (1973)
16.0	Maximum mean temperature to protect embryos hatching in spring.	Hokanson *et al.* (1973)
15.7	Preferred temperature (adult)	Ferguson (1958)
13.0	Maximum food consumption and growth	Baldwin (1957)
12.0	Maximum temperature for stimulation of successful spawning	Hokanson *et al.* (1973)
9.0	Maximum temperature for optimal spawning activity, gamete viability, and embryo survival	Hokanson *et al.* (1973)
6.0	Optimum temperature for hatch	Hokanson *et al.* (1973)

Table 2.3b. Responses of rainbow trout and brown trout to various temperatures.

Temp.(°C)	Fish Response	Reference
Rainbow Trout		
26.5	Upper lethal temperature (juveniles)	Alabaster & Welcomme (1962)
18 - 19	Preferred temperature	McCauley & Pond (1971)
		Cherry *et al.* (1975)
17-19	Optimum temperature for growth(juveniles)	IJC (1978)
9	Optimum temperature for spawning	IJC (1978)
5 -7	Optimum temperature for incubation and hatch	IJC (1978)
Brown Trout		
23.5	Upper lethal temperature	Bishai (1960b)
17.6	Preferred temperature	Ferguson (1958)
15.6	Optimum temperature for growth	Pentelow (1939)
7 - 12	Optimum temperature for incubation and hatch	IJC (1978)
7 - 9	Optimum temperature for spawning	IJC (1978)

Table 2.3c. Responses of smallmouth bass to various temperatures.

Temp. (°C)	Fish Response	Reference
32.0	Upper incipient lethal temperature	Robbins & MacCrimmon (1974)
28.0 - 31.3	Preferred temperatures (lab)	Ferguson (1958) Barans and Tubb (1973) Cherry *et al.* (1975)
26.0	Optimum temperature for growth (juveniles)	Horning & Pearson (1973)
21.4	Preferred temperature in S. Ontario streams	Ferguson (1958)
17.0-18.0	Optimum temperature for spawning	Breder & Rosen (1966)
15.0-17.0	Minimum summer temperatures for self- sustaining populations	Robbins & MacCrimmon (1974)

Table 2.3d. Responses of largemouth bass to various temperatures.

Temp.(°C)	Fish Response	Reference
36.4	Ultimate upper incipient lethal temperature	Hart (1952)
30.0 - 32.0	Preferred temperature (lab)	Ferguson (1958)
26.5 - 32.0	Preferred temperature (L. Monona, Wis.)	Neill (1971)
27.0	Optimum temperature for growth	Coutant (1975)
20.0	Optimum temperature for incubation and hatch	Badenhuizen (1969)
18.9 - 20.0	Optimum temperature for spawning	Coutant (1975)
15.9	Minimum temperature for spawning	Kramer & Smith (1960)
15.0	Fry do not feed	Strawn (1961)
< 10.0	Complete egg die-off	Kramer & Smith (1960)

Table 2.3e. Responses of northern pike and walleye to various temperatures.

Temp.(°C)	Fish Response	Reference
Northern Pike		
29.4 & 33.5	Ultimate upper incipient lethal temperature	Scott (1964) Casselman (1978) resp.
28.0	Growth ceases	Casselman (1978)
19.0 & 21.0	Optimum temperature for growth in weight and length, respectively	Casselman (1978)
12.0	Optimum temperature for incubation and hatch	Hokanson *et al.* (1973)
decline from 10.5 - 7.5	75% mortality during early embryonic development	Hassler (1970)
5.0	100% embryonic mortality	Hassler (1970)
Walleye		
31.6	Ultimate upper incipient lethal temperature	Smith & Koenst (1975)
22.0	Optimum temperature for growth	Smith & Koenst (1975)
20.6 - 23.2	Preferred temperature	Ferguson (1958)
6.0	Optimum temperature for hatch	Smith & Koenst (1975)

3. SOLIDS (SUSPENDED, SETTLEABLE) AND TURBIDITY

3.1 Introduction

Suspended solids (i.e. non-filterable residues) reduce water clarity, and hence, are associated with turbidity. The two terms, however, are not synonymous. Suspended solids are measured in weight concentration units (mg/L) of suspended matter. Turbidity is a measured optical property of water, affecting light transmission, and resulting from the presence of suspended organic and inorganic materials (Thurston *et al.* 1979). The shape, size, and refractive index of the particulate matter influences turbidity, while these factors bear little on the weight concentration of the suspended solids. Turbidity is commonly measured in turbidity units (JTU, FTU)or with the Secchi disk. The Secchi disk reading bears an approximately constant relation to the lower limit at which sufficient light exists for photosynthesis (IJC 1978). Sediments, often measured in linear units, are quite simply formerly suspended solids which have settled and remained on the bottom.

3.2 Criteria

IJC (1978) recommends the following objective for settleable and suspended solids, and light transmission:

> "For the protection of aquatic life, water should be free from substances attributable to municipal, industrial or other discharges resulting from human activity that will settle to form putrescent or otherwise objectionable sludge deposits or that will alter the value of the Secchi disk depth by more than 10 per cent."

EIFAC (1965) recommends the following criteria for concentrations of chemically inert suspended solids in water otherwise satisfactory for the maintenance of freshwater fisheries:

Max. Concentration of Suspended Solids (mg/L)	Remarks
25	High level of protection - no harmful effects on fisheries
80	Moderate level of protection - should maintain good to moderate fisheries but reduced yield compared to first category
400	Low level of protection - unlikely to support good fisheries except at lower concentrations in range
>400	Very low level of protection - only poor fisheries

3.3 Responses of Individual Fish Species

Suspended and settleable solids can affect fish by:

(i) increasing mortality directly, and decreasing growth rate or resistance to disease
(ii) preventing successful embryonic and larval development
(iii) modifying natural movements or migrations
(iv) reducing available food (EIFAC 1965)

Particulate matter may clog gills and impair respiration and excretion, while spawning areas may be destroyed by blankets of sediment (NAS/NAE 1973). Smith (1971) considers excessive sediment deposition the principal cause for reduction of species diversity in Illinois streams. Low standing crops of brook trout in Ellerslie Brook, Prince Edward Island were closely associated with heavy silting (Saunders and Smith 1965). A silt deposition rate of 1.0 mm/day was associated with 97% mortality in pike eggs (Hassler 1970). Quantitative analysis of sedimentation effects on fish populations are extremely limited.

3.4 Species Responses to Turbidity

Turbidity affects underwater vision and, therefore, high levels may reduce the ability of a fish to find and capture prey. Foster (1978) showed that turbidities exceeding 40 JTU substantially reduced the prey attack zone in largemouth bass, and at this level the percentage of empty stomachs in largemouth bass and chain pickerel (*Exos niger*) were significantly greater than at 20 JTU. Activity levels of largemouth bass are reduced at 14-16 JTU compared to 4-6 JTU (Heimstra 1969). Walleye possess a sub-retinal *tapetum lucidum* which improves their visual efficiency under low-light conditions. This provides an advantage over other species under poor light conditions. Ryder (1977) states that standing crops of walleye are usually substantially greater in lakes of low transparency and Kitchell *et al.* (1977) recommend maximum Secchi disk readings of 2 m for optimum walleye habitat.

4. pH

4.1 Introduction

pH is a logarithmic measure of the hydrogen ion activity in a water sample. The carbonate system, composed of carbon dioxide (CO_2), carbonic acid (H_2CO_3), bicarbonate (HCO_3^-) and carbonate ions (CO_3^{2-}), is the principal mechanism regulating pH in natural waters. pH affects the degree of dissociation of weak acids and bases, which in turn affects, the toxicity of many compounds and the solubilities of some metals (Thurston *et al.* 1979). Recently, pH changes in waters due to acid precipitation have received widespread publicity. Waters with a low buffering capacity are most susceptible to pH changes resulting from additions of sulfuric (H_2SO_4) and nitric (HNO_3) acids from the combustion of fossil fuels.

4.2 Criteria

In most productive freshwaters pH ranges from 6.5 to 8.5 (NAS/NAE 1973). IJC (1978) recommends a pH in the range of 6.5 to 9.0 with discharges not changing the pH at the boundary of the designated mixing zone by more than 0.5 units from ambient. NAS/NAE (1973) offers the following criteria for prescribed levels of protection:

- nearly maximum level of protection - pH range 6.5 - 8.5, with no change greater than 0.5 unit outside estimated natural seasonal maximum and minimum.

- high level of protection - pH range 6.0 - 9.0 with no change greater than 0.5 unit outside estimated natural seasonal maximum and minimum.

- moderate level of protection - pH range 6.0 - 9.0 with no change greater than 1.0 unit outside estimated natural seasonal maximum and minimum.

- low level of protection - pH range 5.5 - 9.5 with no change greater than 1.5 units outside estimated natural seasonal maximum and minimum.

Acidification of waters may release free CO_2 which exerts an additional toxic action on fish, and therefore, the above recommendations are valid only if CO_2 is less than 25 mg/L (NAS/NAE 1973).

4.3 Responses of Individual Fish Species

Thurston *et al.* (1979) reproduced the following table from EIFAC (1969):

pH Range	Effect on Fish
5.0-6.0	Unlikely to be harmful to any species unless either the concentration of free carbon dioxide is greater than 20 mg/L, or the water contains iron salts which are precipitated as ferric hydroxide, the precise toxicity of which is not known.
6.0-6.5	Unlikely to be harmful to fish unless free carbon dioxide is present in excess of 100 mg/L.
6.5-9.0	Harmless to fish, although the toxicity of other poisons may be affected by changes within this range.

The two following tables document specific effects of pH levels on sport fishes.

Table 4.1a. Responses of brook trout to various levels of pH.

pH	Fish Response	Reference
9.8	Upper lethal limit	Daye & Garside (1975)
< 6.5	Reduced hatchability and growth with continual exposure	Menendez (1976)
5.0 - 5.8	Behavioural signs of distress in fish acclimated to pH7.5-8.5	Falk & Dunson (1977)
4.5 - 5.6	Populations severely degraded	Butleretal. (1973)
5.0	Number of viable eggs reduced	Menendez (1976)
4.6 - 4.9	Lethal to all trout confined in stream below pyritiferous rock roadfill	Huckabee *et al.* (1975)
4.2	100% mortality in 49 hr in fish confined to cages	Dunson & Martin (1973)
decline from 8.0 to 4.0	100% mortality after hatching	Trojnar (1977)
3.5	Lower lethal limit (compared to 4.75forrainbow trout embryos; Kwain (1975)	Day & Garside (1975)

Table 4.1b. Responses of non-salmonid sport fishes to various levels of pH.

pH	Fish Response	Reference
Smallmouth and Largemouth Bass		
10.3-10.8	24h LC_{50} (juveniles; 1 -10 cm)	Calabrese (1969)
decline from 8.6 -6.0 and increase from 8.0-9.3	Rapid changes tolerated by juveniles (4 - 6 cm)	Wiebe (1931)
5.5	Reproductive failure(smallmouth bass)in George Lake, Ontario	Beamish (1975)
3.9-4.2	24 h LC_{50} (juveniles:1 -10 cm)	Calabrese (1969)
Rock Bass		
4.7-5.2	Reproductive failure in George Lake, Ontario	Beamish (1975)
4.4	Reproduction inhibited	Ryan & Harvey (1977)
Northern Pike		
4.7-5.2	Reproductive failure in George Lake, Ontario	Beamish (1975)
Walleye		
5.2-5.8	Reproductive failure in George Lake, Ontario	Beamish (1975)

5. METALS

5.1 Introduction

The toxicity of metals to fish depends on numerous aspects of water quality including pH, hardness and other chemical compounds. NAS/NAE (1973) recommends that specific water quality criteria be based on the total amount of the given metal regardless of its chemical state or form, since the variety of metals in water which determine toxicity, shift with water quality often in unpredictable ways. There remains considerable argument about acceptable criteria for many metals (Thurston *et al.* 1979). Metals (e.g. cadmium) are often more toxic to freshwater invertebrates than fish, but destruction of parts of the food resource base will ultimately affect fish at the higher trophic levels. Metal concentrations having devastating effects on lower trophic levels may be well below those acutely toxic to fish.

5.2 Aluminum

Aluminum is one of the most common elements. As an amphoteric metal in aqueous environments, it may be in solution as a weak acid, or present in the form of a flocculent hydroxide, depending on pH. Aluminium sulphate (alum) is used in water treatment as a coagulant for suspended solids, including colloidal materials and micro-organisms. Recent findings indicate the toxicity of aluminum may have been previously underestimated (NAS/NAE 1973).

In fresh water, the toxicity of aluminum salts varies with hardness, turbidity and pH. Aluminum salts were slightly soluble at neutral pH with 0.05 mg/L being dissolved, a level which had no sublethal effects on fish (Freeman and Everhart 1971). However, at pH 9.0, at least 5 mg/L aluminum dissolved killing rainbow trout within 48 h. Subsequently, Everhart and Freeman (1973) found 5.2 mg/L aluminum at pH 8.0 drastically reduced feeding activity of rainbow trout over 24 h.

5.3 Arsenic

Arsenic is a metalloid element, having characteristics of both metals and non-metals, occurring naturally as arsenides or arsenopyritis. It is sparingly soluble in water depending on physical properties of the medium and presence of other compounds (Thurston *et al.* 1979). Arsenic is used in manufacturing adhesives, paper, glass and ceramics, while its compounds are important in formulating pesticides, paints, wood preservatives, and as a growth stimulant in animal feed.

Arsenic is a cumulative poison, thought to be especially hazardous to humans. In freshwater organisms arsenic bio-accumulates but apparently does not biomagnify in the food web (Penrose *et al.* 1977). The toxicity of arsenicals is related to the biological half-life which is very much determined by the chemical form and oxidation state of the arsenical involved (Thurston *et al.* 1979).

For public surface water supplies EPA (1976) recommends criteria of 50 µg/L to protect human health. They, along with IJC (1977) recommend this criteria for protection of aquatic life but Thurston *et al.* (1979) severely criticize this criteria as lacking in scientific evidence and likely too high for certain compounds. Apparently, there exists no widely accepted criteria for arsenic to protect freshwater animals and Thurston *et al.* (1979) recommend further research on various chemical forms of arsenic on fish, particularly in larval fish and sensitive species.

From specific studies, Paladino (1976) showed that 50 µg/L arsenic (A_5^{3+}) caused 100% mortality in muskellunge swim-up fry while Cardwell *et al.* (1976) determined LC50s for sodium arsenite of 32,000 µg/L (336 h) for goldfish and 18,000 µg/L (262 h) for brook trout. Lambou and Lim (1970) considered 700 to 7000 µg/L arsenic as safe concentrations for several fish species. In Great Lakes fishes, background arsenic levels range from 5.6 to 8.0 µg/L (Lucas *et al.* 1968), but fish exposed to gold mine effluents had concentrations as high as 4400 µg/L (Falk *et al.* 1973).

5.4 Cadmium

Cadmium is a divalent metal with widespread industrial importance. It is often associated with lead and zinc, the mining of the latter being the principal source of cadmium. It is an extremely toxic cumulative poison. Cadmium toxicity depends on water hardness. Harder waters have a greater complexing capacity and subsequently decreased cadmium toxicity.

IJC (1977) and MOE (1978) recommend that concentrations of total cadmium in an unfiltered sample not exceed 0.2 µg/L to protect aquatic life. Thurston *et al.* (1979) list the following criteria for filtered (45 micron filter) water samples at various hardness levels.

Hardness	Soluble Cadmium (µg/L)	
mg/L as $CaCO_3$	Sensitive species*	Less sensitive species
0 - 35	0.4	0.8
35 - 75	1.0	2.0
75 - 150	2.5	5.0
150 - 300	6.0	12.0
>300	15.0	30.0

* reproductive stages of trout are extremely sensitive to cadmium toxicity. In addition zooplankton which are important food items are also extremely sensitive (IJC 1977).

Pre-exposure or acclimation to cadmium during embryonic development, increases the resistance of rainbow trout to cadmium (Goettl & Davies 1976).Table 5.4 reproduced from Thurston *et al.* (1979) summarizes toxic effects of cadmium to freshwater fish.

Table 5.4. Summary of acute and chronic Cadmium toxicity data on freshwater fishes (from Thurston *et al.* 1979).

(M=mortality, G = growth, EE = eggs exposed, NE=eggs not exposed, H = hatchability, S=spawning, R=reproductive impairment).

Species	Hardness (mg/L as $CaCO_3$)	96 h LC_{50} (µg/L)	Long-term exposure		Reference
			Limits on MATC (µg/L)	Basis of effect	
Rainbow trout	290	9 (7-day)			Ball 1967a
Rainbow trout	31		0.7 - 1.5 [b]	M	Davies 1976
Rainbow trout	28	3.0	3.4 - 7.1 [a]	M	Goettl and Davies 1976
Rainbow trout	328	>40.0	13.5 - 21.0 [b]	M	Davies 1976
Brook trout	44	12 - 180 [c]	1.7 - 3.4[a]	M	Benoit *et al.* 1976
Brook trout	44	82 - 405 [d]			Benoit *et al.* 1976
Brook trout	44		1.1 - 3.8 [b]	G	Eaton *et al.* 1978
Brook trout	37		1.0 - 3.0 [b]	G	Sauter *et al.* 1976
Brook trout	37		3.0 - 6.0 [b]	M&G	Sauter *et al.* 1976
Brook trout	188		7 - 12 [b]	M&G	Sauter *et al.* 1976
Brown trout	44		3.8 - 11.7 [b]	C	Eaton *et al.* 1978
Brown trout (late eyed embryos)	44		1.1 - 3.7[b]	G	Eaton *et al.* 1978
Northern pike	44		4.0 - 12.9 [b]	G	Eaton *et al.* 1978
Channel catfish	37		11 - 17 [b]	M	Sauter *et al.* 1976
Channel catfish	185	12-17 [b]		G	Sauter *et al.* 1976
Channel catfish	185		>59[b]	M	Sauter et al. 1976
Smallmouth bass	44		4.3 - 12.7[b]	G	Eaton *et al.* 1978
White sucker	44		4.2 - 12.0 [b]	G	Eaton *et al.* 1978
Walleye	37		9 - 25[b]	M	Sauter *et al.* 1975
Walleye	187		>87 [b]	M	Sauter *et al.* 1976
Bluegill	230		31 - 80 [b]	M	Eaton 1974

[a] The maximum acceptable toxicant concentration - between the concentration tested having no observed effect and the next highest concentration having a significant toxic effect during a life-cycle fish toxicity test (Mount and Stephan 1967).

[b] These numbers are not true MATC's as defined above, but are considered to be good estimates of the MATC (McKim 1977).

[c] 95% mortality in 96 h at these concentrations with disturbance of fish.

[d] 100% survival in 96 h at these concentrations with no disturbance of fish.

5.5 Chromium

Chromium is rarely found in natural waters but may enter as a contaminant from plating wastes, production of paints and dyes, and from cooling tower discharges to which it is added to control corrosion (IJC 1977). Hexavalent chromium (Cr^{6+}) appears more acutely toxic to fish than the trivalent (Cr^{3+}) form (IJC 1977). For public water supplies IJC (1977) recommends a maximum of 50 µg/L, while MOE (1978) and EPA (1976) suggest a maximum of 100 µg/L will protect aquatic life. However, Thurston *et al.* (1979) suggests this latter level may be suitable for Cr^{3+} but not for Cr^{6+}.

Benoit (1976) determined a 96 h LC_{50} of 5900 µg/L with a safe level of 200 µg/L for brook trout in soft water. Values for rainbow trout were 69,000 and 200 µg/L for 96 h LC_{50} and safe level respectively. For bluegills, Pickering and Henderson (1966) found 96 h LC_{50}'s of 118,000 µg/L in soft water (hardness 20 mg/L) and 133,000 µg/L in hard water (hardness 360 mg/L).

Aquatic invertebrates are more sensitive to chromium than fish and using this basis NAS/NAE (1973) recommends a criteria of 50 µg/L total chromium.

5.6 Copper

Copper is a native metal occurring in various mineral forms as cuprite and malachite. It is an essential trace element for the propagation of plants and metabolism of animals. Copper is mined for use in electrical products, metal plating, alloys, and heat exchangers which are potentially large sources of copper in surface waters where cooling waters are discharged. The oxide and sulfate forms are used in pesticides.

Copper concentrations in aquatic life are generally low with no apparent bio-accumulation (IJC 1978). Juvenile fish, algae, and aquatic invertebrates are more susceptible to copper than adult fish (EPA 1976); Copper at concentrations near the LC_{50} values for adult fish will have a devastating impact on lower life forms (Thurston *et al.* 1979).

IJC (1978) and MOE (1978) recommend total concentrations of copper in unfiltered water should not exceed 5.0 µg/L to protect aquatic life.

However, Thurston *et al.* (1979) point out that copper toxicity is related to pH, alkalinity, hardness and organic content of water, and hence different natural waters may require different criteria depending on the above parameters.

Table 5.6 documents some effects of copper exposure on brook and rainbow trout, Atlantic salmon and bluegill.

Table 5.6. Responses of brook and rainbow trout, Atlantic salmon and bluegill to various concentrations of copper.

Copper (µg/L)	Hardness (mg/L $CaCO_3$)	Fish Response	Reference
Bluegill			
740	20	48 h LC_{50}	Pickering & Henderson (1966)
21 - 40	--	Larval mortality	Benoit (1975)
Atlantic Salmon			
125	8-10	96 h LC_{50} for parr @18 - 21°C; Humic acid concentration during test: 4.5 - 50 mg/L	Wilson (1972)
17 - 21	20	Avoidance by adults moving upstream	Sprague *et al.* (1965)
2.3	18	Avoidance threshold in lab	Sprague (1964)
Rainbow Trout			
270	320	48 h LC_{50} @17°C for yearlings	Herbert & Vandyke (1964)
64	4	48 h LC_{50}	Bilinski & Jonas (1973)
Brook Trout			
100	46	96 h LC_{50} @12°C for juveniles	McKim & Benoit (1971)
50	14	10 day LC_{50} @ 15°C	Sprague (1968)
32.5	45	Survival decreased in yearlings with B month exposure from 93% (control) to 43%. 100% alevin mortality in 4 months. Embryo hatch premature	McKim & Benoit (1971)
9.5 - 17.5	45	Decreased survival and growth of juveniles	McKim & Benoit (1971)
9.0	45	Marked reduction in feeding frequency Frequency of cough re3ponse increased over 0 and 6 µg/L exposures	Drummond *et al.* (1973)

5.7 Iron

Iron is the fourth most abundant element by weight, and it is present in most rocks and soils. In addition to natural weathering of rocks and soils and iron bearing groundwater, important sources of iron in the aquatic environment are; mine drainage waters, industrial wastes and corrosion of steel products. Iron is an essential trace element vital in the mechanism of oxygen transport in blood.

In water, iron usually exists in ferrous (Fe^{2+}) or ferric (Fe^{3+}) forms. In the absence of dissolved oxygen, soluble ferrous iron predominates. Under aerobic conditions non soluble ferric iron predominates. This form is readily precipitated as hydroxides.

EPA (1976) sets 1.0 mg/L total iron as the maximum concentration to protect aquatic life. However, Thurston *et al.* (1979) and IJC (1978) consider this level too high and the latter group along with MOE (1978) recommend maximum total iron concentration of 0.3 mg/L in unfiltered water. Even this level may not protect the mayfly (*Ephemerella subvaria*), an important aquatic food item, which has a 96 h LC_{50} for iron of 0.32 mg/L (Warnick and Bell 1969).

Ferric hydroxide precipitates settling on the bottom interfere with the respiration of fish embryos as well as clogging gills in adult fish (IJC 1978). Brook trout embryos were affected through reduced hatchability only at concentrations above 12 mg/L (Sykora *et al.* 1975), while juveniles appeared safe from mortality at iron concentrations up to 7.5 to 12.5 mg/L. A 50% reduction in the hatchability of fathead minnow embryos resulted from 1.5 mg/L iron (Smith *et al.* 1973), and 1.0 - 2.0 mg/L iron was lethal to northern pike (Duodoroff and Katz 1953). A ferric hydroxide floc should not form at total iron concentrations less than 0.3 mg/L (NAS/NAE 1973).

5.8 Lead

Man introduces lead into aquatic ecosystems through its production and use in gasolines, paints, pipes, roofing materials, shotgun pellets and other ammunition, and mining and refining processes. The concentration of lead in water is generally low due to its low solubility (IJC 1977). Lead solubility is governed by alkalinity, pH and water hardness. These factors therefore, influence the toxicity of lead with toxicity declining with increased alkalinity (MOE 1978). Lead is a cumulative poison with concentrations in fish liver up to 1.2 mg/L for unpolluted waters (Warren *et al.* 1971) and 3.2 mg/L in lead polluted waters (Falk *et al.* 1973).

Criteria for lead must take water hardness into account. MOE (1978) suggest that the total lead concentration should not exceed those listed below:

Hardness ($CaCO_3$, mg/L)	Maximum acceptable lead concentration (mg/L)
< 20	0.005
20 - 40	0.010
40 - 80	0.020
> 80	0.025

Thurston *et al.* (1979) recommend slightly different values based on life-cycle exposures to brook and rainbow trout:

Hardness, mg/L as $CaCO_3$	Lead Criterion, mg/L Total Lead
0- 30	0.004
30 - 100	0.025
100 - 300	0.05
>300	0.10

IJC (1977) recommends that concentrations of total lead in an unfiltered water sample should not exceed 0.010 mg/L for Lake Superior, 0.020 mg/L for Lake Huron, and 0.025 mg/L for the remaining Great Lakes.

Prolonged exposures of rainbow trout juveniles to lead at 0.013 - 0.020 mg/L in soft water (hardness 27 mg/L) or 0.120 - 0.360 mg/L in hard water (hardness 354 mg/L) cause "black-tails" and spinal curvatures (lordosis and scoliosis) (Davies & Everheart, 1972). Table 5.8 reproduced and slightly modified from Thurston *et al.* (1979) summarizes lead toxicity to brook and rainbow trout, channel catfish and bluegill.

Table 5.8. Summary of acute and chronic lead toxicity data on some freshwater fish.

Species	Water Hardness (mg/L as $CaCO_3$)	Acute 96 hr LC_{50} (mg/L)	Chronic Limits on MATC[a] (mg/L)	References
Brook trout	45	4.1	0.058 - 0.119	Holcombe *et al.* (1976)
Rainbow trout	28	1.2	0.004 - 0.008[b]	Davies *et al.* (1976)
Rainbow trout	350	471	0.120 - 0.360[b]	Davies *et al.* (1976)
Rainbow trout	36	---	0.071 - 0.146[b]	Sauter *et al.* (1976)
Channel catfish	36	---	0.075 - 0.136[b]	Sauter *et al.* (1976)
Bluegill	36	---	0.070 - 0.120[b]	Sauter *et al.* (1976)

[a] Maximum acceptable toxicant concentration: the hypothetical toxic threshold concentration between the highest concentration tested having no observed effects and the next higher toxicant concentration having significant toxic effects during a life-cycle fish toxicity test (as set forth in Mount and Stephan 1967).

[b] These numbers are not true MATC's as defined above, but are considered to be good estimates of the MATC (McKim 1977).

5.9 Mercury

Mercury can enter aquatic environments by leaching from geological formations, the atmosphere, industrial and municipal waste disposal and land drainage. It is estimated that mercury polluted water bodies continue to contaminate fish for 10 to 100 years after the pollution has ceased (NAS/NAE 1973). Mercury present in fish is mostly methylmercury which results from methylmercury in the environment (Thurston *et al.* 1979). Certain microorganisms in sediment are able to convert other forms of mercury to highly toxic methyl and dimethyl forms (Jensen & Jernelov 1969). Any form of mercury is thus, potentially hazardous to the environment. Due to rapid accumulation and slow elimination (Lockhart *et al.* 1973), fish may bioaccumulate mercury 10,000 times above the levels found in the surrounding water. For example, fish may accumulate mercury to levels above 1 µg/L from waters containing as little as 0.018 µg/L mercury as methylmercury (Olson *et al.* 1975).

IJC (1977) and MOE (1978) recommend that concentrations of total mercury in filtered water samples should not exceed 0.2 µg/L nor should the concentration of total mercury in whole fish exceed 0.5 µg/g on a wet weight basis. The criterion set by EPA (1976) for freshwater aquatic life and wildlife is 0.05 µg/L.

A large portion of the mercury in aquatic systems is associated with sediments, and therefore, its concentration in water can be affected by suspended solids (IJC 1977). It is nearly impossible to correlate total mercury in unfiltered water with the concentrations of methyl mercury which accumulate in fish (IJC 1977). For this reason they state that, "total mercury in unfiltered water has only marginal usefulness in deriving environmental quality criteria, and therefore, the measurement of mercury in biological organisms represents a significantly more persuasive criterion."

Crayfish accumulate significant amounts of methylmercury and that they may be suitable for an immediate measure of the net methylation rate has been suggested by IJC (1977). The highly toxic nature of mercury due to its bioaccumulation, must be considered when discussing either mercury levels in water or in potential prey organisms. Table 5.9 documents some effects of mercury on sport fishes.

Table 5.9. Responses of brook and rainbow trout to various concentrations of mercury.

Hg µg/L	Fish Response	Reference
0.03	Accumulation of 0.96 µg/g in brook trout exposed for239 days.	McKim *et al.* (1978)
0.93	Nearly 100% mortality, and deformities in 2nd generation brook trout exposed for108 weeks (9.5 µg/g mean muscle residue in fish that died).	McKim et al. (1978)
2.0	Fed daily to rainbow trout for 1 year; then given uncontaminated food for six months: mean mercury concentration in muscle 1.02 µg/g	Hartman (1978)
2.93	Deformities and 88% mortality in brook trout adults with 39 week exposure. (23.5 µg/g mean muscle residue in fish that died)	McKim *et al.* (1978)
3.0	Increased cough response in brook trout with 5 day exposure	Drummond *et al.* (1974)
5.0	Retarded performance of learning tasks in rainbow trout fed this level daily for 1 year	Hartman (1978)
10.0	Retarded performance of learning tasks in rainbow trout fed this level every 5th day for 1 year	Hartman (1978)

5.10 Nickel

Nickel enters water indirectly by the burning of fossil fuels, and directly through mining and smelting operations, manufacturing of nickel bearing pigments, alloys and plated metals (IJC 1978). It is not an essential element or nutrient for plants or animals and its principal biological activity is that of a toxicant (IJC 1978).

The acute toxicity of nickel to fish is less than that of zinc or copper, (Rehwoldt *et al.* 1971) , and it varies greatly with species and water quality (see Section 8) being more toxic in soft than hard water. IJC (1978) and MOE (1978) recommend that concentrations of total nickel in unfiltered water samples should not exceed 25 µg/L. The EPA (1976) criterion of 0.01 of the 96 h LC_{50} for freshwater and marine life has been criticized by Thurston *et al.* (1979) as being inadequate. The limited amount of data on nickel refers to acute toxicity with the exception of Pickering (1974) who found reduced egg production and hatchability in fathead minnows at a nickel concentration of 730 µg/L. Table 5.10 lists 96 h LC_{50} values for nickel.

Table 5.10. 96 h LC_{50}'s for nickel on selected fish species.

Nickel µg/L	Temp. °C	D.O. mg/L	pH	mg/L	Species	Reference
39,600	25	7.8	8.4 - 7.4	360	Bluegill	Pickering & Henderson (1966)
10,600	17	6.5	7.8	53	Carp	Rehwoldt *et al.* (1972)
8,100	17	6.5	7.8	53	Pumpkinseed	Rehwoldt *et al.* (1972)
6,200	17	6.5	7.8	53	White perch	Rehwoldt *et al.* (1972)
5,270	25	7.8	7.5	20	Bluegill	Pickering & Henderson (1966)

5.11 Zinc

Various forms of zinc are used in metal fabricating, metal coatings, batteries, paints, varnishes, rubber, soaps, medicines, and pulp and paper production. Zinc may enter water directly from the mining of zinc ore and the corrosion of metallic zinc, or indirectly from the fallout from burning fossil fuels containing zinc (IJC 1978). Zinc is an essential element for plant and animal growth, reproduction and metabolism.

In terrestrial systems zinc is relatively non-toxic (IJC 1978) except occasionally to plants growing in soils enriched with zinc as a result of mining operations. In aquatic systems, zinc is more toxic to freshwater fishes than algae or invertebrates (IJC 1978). The toxicity of zinc is governed by water quality and is enhanced when combined with other metals (see Section 8), particularly cadmium and copper (IJC 1977).

IJC (1978) and MOE (1978) recommend that concentration of total zinc in an unfiltered water sample should not exceed 0.03 mg/L to protect aquatic life. Thurston *et al.* (1979) recommend the following criteria related to water hardness and based on data from life-cycle exposures of four fish species and one invertebrate species.

Hardness, mg/L as $CaCO_3$	Zinc Criterion, mg/L Total Zinc
0 - 75	0.05
75 - 150	0.05
150 - 300	0.10
300 - 400	0.30
>400	0.60

Table 5.11 documents effects of zinc (mostly 96 h LC_{50}'s) on sport and other fishes.

Table 5.11. Responses of fish to various concentrations of zinc (96h LC_{50}'s unless otherwise stated).

Zinc mg/L	pH	Hardness ($CaCO_3$) mg/L	Fish Size	Reference
Brook Trout				
2.5	7.3 - 7.7	45	19.0 g fish	Holcombe & Benoit (1978)
2.09	7.3 - 7.7	45	3.9 g fish	Holcombe & Benoit (1978)
1.38	7.3 - 7.7	45	3.0 g fish	Holcombe & Benoit (1978)
Rainbow Trout				
7.21	7.8	333	juveniles	Sinley *et al.* (1974)
0.43	6.8	26	juveniles	Sinley *et al.* (1974)
0.04			0% hatch	Afleck (1952)
0.01			46% fry survival	Afleck (1952)
0.003			98% fry survival	Afleck (1952)
Bluegill				
40.9	7.5	360	1-2 g fish	Pickering & Henderson (1966)
10.6	7.8	46	37 g fish	Cairns *et al.* (1971)
5.4	7.5	20	1-2 g fish	Pickering & Henderson (1966)
0.235		51	decreased spawning and 100% fry mortality	Sparks *et al.* (1972)
Other Species				
20.0	7.8	53	Pumpkinseed 520cm	Rehwoldt *et al.* (1971)
14.3	7.8	53	White perch ≤20cm	Rehwoldt *et al.* (1971)
7.8	7.8	53	Carp ≤20cm	Rehwoldt *et al.* (1971)
0.24			Migration of adults Atlantic Salmon prevented	Sprague *et al.*(1965)
0.054			Avoided by juvenile Atlantic Salmon in lab	Sprague *et al.*(1965)

6. PESTICIDES

Of the thousands of pesticide formulations comprising nearly 900 chemicals, many present hazards to non-target organisms. In Ontario about 490 registered active ingredients are used in 3100 products scheduled and sold (R. Frank, personal communication). Pesticides can enter the water through agricultural and urban runoff, industrial and domestic discharges and from atmospheric drift and precipitation. Effects of individual pesticides on fish are documented in Table 6, however, within natural systems these chemicals are involved in many complex reactions. Fortunately, many pesticides with high bioaccumulation factors are no longer in use. However, because of their low depredation rates, residues from many still persist in aquatic environments.

To protect aquatic life, human consumers and fish-eating birds, IJC (1977, 1978) and MOE (1978) objectives and EPA (1976) criteria established for some pesticides are listed in Table 6. IJC (1978) recommends that concentrations of unspecified, non-persistent pesticides should not exceed 0.05 of the 96 h LC_{50} for any local sensitive species. For pesticides with no apparent recommended criteria, we have calculated their maximum acceptable concentrations using this application factor to 96 h LC_{50}'s given for various sport fish species (Table 6).

Under normal situations, it is unlikely that pesticide concentrations, other than algicides, would be close to the criteria levels. If levels are recorded near maximum acceptable concentrations, a spillage or incorrect type of application should be suspected (R. Frank, personal communication).

Table 6. Pesticides, their use and effects on aquatic organisms, and recommended objectives (maximum acceptable concentrations) in water (µg/L) and fish tissue (µg/g).

	Use	Recommended Objectives Water µg/L	Fish µg/g	Agency	Comments (all values in µg/L)	Reference[2]
Algimycine	algicide				Brown trout 48h LC_{50} = 20,000	McKim *et al.* (1976)
Atlacide	(sodium chlorate) soil sterilant, general vegetation control in non-crop areas				Brown trout 48h LC_{50} = 7200	McKim *et al.* (1976)
Acrolein	(trade names - Aqualin and Hydrothal) aquatic weed control	5.0*			Rainbow trout and Brown trout 24 h LC_{50}'s = 140 and 46, respectively largemouth bass and bluegill 96 h $_{LC50}$'s =160 and100	EPA (1974)
Alachlor	herbicide for corn, used on its own or with other herbicides	115		IJC	Rainbow trout and bluegill 96h LC_{50}'s 1000 and 5800 respectively	EPA (1974)
Aldrin/Dieldrin**		0.001	0.3	IJC		
Atrazine	herbicide for corn, applied in spring and early summer	25		IJC	Rainbow trout 96h and bluegill 46h LC_{50} = 4600 and 26000 respectively	EPA (1974)
					For growth and reproduction - Maximum Acceptable Toxicant Concentration - bluegills 90 -500 and brook trout 60 - 120	Macek *et al.* (1976)
Butylate	(trade name -Sutan), corn herbicide, used alone or in combination with other herbicides	210-345 *			Rainbow trout and bluegill 96 h LC50's = 4200 and 6900 respectively	EPA (1974)
Captan	fungicide, very common, used on golf courses, lawns orchards, etc.				Fish sp? LC_{50}= 130 (bluegill or rainbow trout)	Weber (1977)
Chlordane	widely used insecticide for spot treatments in homes and gardens, wasp nests, etc.	0.06		IJC MOE	Rainbow trout and bluegills 96h LC_{50} = 44 and 16-85 respectively	Anon (1977)
Chlorpyrifos	(trade name - Dursban), mosquito control(larvae and adults), also household pests and agricultural insecticide (tobacco)	0.001		MOE		
Copper sulphate	used to control nuisance algal growth	5.0*			More toxic in soft water (see Section 8) in water with 20 - 25 mg/L $CaCO_3$, Brook trout and bluegill 96h LC_{50} = 100 Bluegill larvae die at 40; no effect conc. = 20	McKim *et al.*(1976)

Cutrine	aquatic algae control, contains copper	9.9*			Brown trout 96h LC_{50} = 199(copper)	Simonin and Skea (1977)
Cyprazine	corn herbicide, on its own or with other herbicides	310		IJC		
Dalapon	herbicide (soil sterilant) grasses control, low use	110		MOE	Fish sp? LC_{50} 115,000 (Cyprinid)	Weber (1977)
Diazinon	insecticide, main use in homes (fleas) and gardens (white grub), also fruits, vegetables, field crops and ornamentals	0.08		IJC MOE	Brooktrout and bluegill 96h LC_{50}= 770 and 460 respectively. Does not appreciably accumulate in biological tissue.	IJC (1978)
D.D.T.**		0.003	1.0	IJC	Brooktrout and rainbow trout 96h LC_{50} = 7 - 12 and 1.72 respectively	Post and Schroeder (1971)
Dicamba	(trade name Banvel), herbicide for parks and gardens (blue grass), used in spring and fall	200		MOE		
Diquat	(trade name Reglone 'A')- aquatic vegetation control, spring and early summer crops, short-term soil sterilant. Also used to control external infections and gill disease in fish	0.5		MOE	Brown trout 96h LC_{50} =300 Brown trout fingerlings 96h LC_{50}= 20,400	McKim *et al.* (1978) Simonin and Skea (1977)
Diuron	long term soil sterilant, Industrial use (weed control for pathways e.g. Hydro Power Plants, etc.) Limited orchard use.	1.6		MOE	Fishsp? LC_{50}= 4300 (bluegill or rainbow trout)	Weber (1977)
Endosulphan	used for insect control on fruit and vegetables	0.001		EPA, IJC, MOE		
Endrin**		0.002	0.3	IJC	Brooktrout and rainbow trout 96h LC_{50}= 0.35-0.59 & 0.4µg/L, respectively	Post and Schroeder (1971)
Ethion	mite control on fruit and vegetables	0.0135		IJC		
Fenthion	(trade name Baytex)- mosquito, fly control(larvae and adults), also structural pest control and some use on horticultural and ornamental plants	0.006		MOE		
Guthion	insecticide, short life, very toxic. Horn worm control on tobacco, also fruit and vegetables	0.005 0.01		EPA, IJC MOE		
Heptachlor**		0.01	0.3	EPA, IJC		
Lindane		0.01	0.3	EPA,IJC	Fish sp? LC_{50}= 18 (bluegill or rainbow trout)	Weber (1977)

Malathion	insecticide, used all year adult mosquitos, trees and shrubs (tent caterpillar). Limited use, sweet corn	0.1		EPA, MOE	Brook trout and rainbow trout 96h LC_{50} = 120 -130	Post and Schroeder (1971)
Methoxychlor	much the same as Malathion	0.04		IJC, MOE		
Mirex	control of fire ant; also used as a flame retardant	0.005	0.005	IJC	Should not exceed detection limit (0.005 µg/L)	IJC (1978)
Parathion	insect control on fruits and vegetables	0.04 0.008		EPA, IJC	Brook trout and bluegill 96h LC_{50} = 1700 & 500 respectively	IJC (1978)
Pyrethrum	insecticide, wide domestic and agricultural use	0.01		MOE	Brown trout 24h LC_{50} = 1.2 - 4.9 µg/L	McKim *et al.* (1978)
Simazine	wide use, soil sterilant, control broadleaf weeds	10.0		MOE		
Toxaphene**		0.005 0.008		EPA IJC		
2,4-D	aquatic weed control, broadleaf weeds (lawns, paths, etc.)	4.0		MOE		
2,4,5-T	herbicide, usually used in combination with 2,4-D. Used in forestry, brush control, roadsides, etc.				Fish sp? LC_{50} = 500 (bluegill or rainbow trout)	Weber (1977)

* Calculated maximum acceptable concentrations (0.05 of the 96 h LC_{50}, IJC 1978).

** Pesticides not actively used in Ontario (MOE 1978).

[1] EPA (EPA 1976), IJC (1977, 1978), MOE (1978).

[2] Refers to Source and not original authors in all cases.

7. OTHER TOXIC SUBSTANCES

7.1 Ammonia

Ammonia is present in most waters as a biologically active alkaline compound, composed of nitrogen and hydrogen, and is a product of the biological degradation of nitrogenous organic matter. Ammonia is a pungent, colourless, gaseous compound highly soluble in water (EPA 1976). High concentrations of ammonia are primarily due to municipal sewage effluents, but other sources include runoff from animal feed lots, and other agricultural practices, industrial discharges, and cleaning operations using ammonia or ammonia salts. Also, effluents from fish rearing facilities often contain high ammonia levels derived from metabolic by-products of fishes (NAS/NAE 1973).

Un-ionized ammonia (NH_3) is generally considered the toxic component of ammonia solutions, and ionized ammonia has little or no toxic effect (but see Thurston *et al.* 1979). For this reason, criteria for ammonia are based on maximum acceptable levels of un-ionized ammonia. To protect aquatic life, unionized ammonia should not exceed 0.02 mg/L (EPA 1976, IJC 1978, MOE 1978). The percentage of total ammonia in solution in the un-ionized form depends on pH and temperature, and therefore, these parameters must be known before concentrations of un-ionized ammonia can be determined. Since the percentage of unionized ammonia increases with increased temperature and pH (Table 7.1a), ammonia toxicity also increases with increased temperature and pH. If these parameters fluctuate, the toxicity of ammonia may be difficult to predict, and it may be necessary to conduct bioassays using the receiving water. EPA (1976) recommends that un-ionized ammonia concentrations should not exceed 0.05 of the 96 h LC_{50}.

Ammonia concentrations below those which have adverse effects on fish are unlikely to be toxic to other aquatic organisms (EIFAC 1970). Table 7.1b documents some acute and chronic responses of fish to un-ionized ammonia. From their experiments and results of others, Thurston *et al.* (1978) conclude that acute toxicity tests on salmonids generally fall within 0.2 - 0.8 mg/L NH_3, compared to 0.4 - 4.0 mg/L for other species.

Table 7.1a. Percentages of un-ionized ammonia in aqueous ammonia solutions for different pH and temperature. (Source, MOE 1978).

pH	Temperature (°C)					
	5	10	15	20	25	30
6.0	0.013	0.019	0.027	0.040	0.057	0.081
6.5	0.040	0.059	0.087	0.13	0.18	0.25
7.0	0.13	0.19	0.27	0.40	0.57	0.80
7.5	0.39	0.59	0.86	1.2	1.8	2.5
8.0	1.2	1.8	2.7	3.8	5.4	7.5
8.5	3.8	5.6	8.0	11.0	15.0	20.0
9.0	11.0	16.0	22.0	28.0	36.0	45.0
9.5	28.0	37.0	46.0	56.0	64.0	72.0
10.0	56.0	65.0	73.0	80.0	85.0	89.0

Example

At 20°C and pH 8.0, a total ammonia concentration of 0.5 mg/L would give an un-ionized concentration of 0.5 X 3.8/100 = 0.019 mg/L.

Table 7.1b. Responses of fish to various concentrations of un-ionized ammonia.

NH_3 mg/L	Fish Response	Reference
6.0 - 7.4	Bluegill 48 h LC_{50}	McKee & Wolf (1963)
2.5	Brook trout 24 h LC_{100}	McKee & Wolf (1963)
0.5 - 0.8	Cutthroat trout fry 96 h LC_{50}	Thurston *et al.* (1978)
0.3 - 0.6	Cutthroat trout fry 36 day LC_{50}	Thurston *et al.* (1978)
0.4 - 0.58	Rainbow trout 24 h LC_{50}	Herbert & Shurben (1965)
0.29	Perch 96 h LC_{50}	Ball (1967b)
0.05	(NH_3-N) Rainbow trout sac fry growth rate and development inhibited after exposure from fertilization for 67 - 75 days	Burkhalter & Kaya (1977)
<0.01	(NH_3 -N) Rainbow trout reduced growth rate and severe pathological changes in gill and liver	Smith & Piper (1975)
0.005	Rainbow trout, 6 weeks exposure caused gill hyperplasia	Burrows (1964)

7.2 Carbon Dioxide

In water carbon dioxide exists either by entering into the bicarbonate buffering system at various concentrations depending on the pH, or as free carbon dioxide. This latter form affects the ability of fish to extract oxygen, although concentrations of free carbon dioxide that impair oxygen uptake are generally higher than the levels existing even in polluted waters (Duodoroff and Shumway 1970). Free carbon dioxide rarely exceeds 20 mg/L (NAS/NAE 1973). Hart (1945) found that fish could still extract dissolved oxygen almost completely at free carbon dioxide concentrations as high as 60 mg/L.

A free carbon dioxide concentration of 45 mg/L has been reported as lethal to trout while 20 mg/L may be lethal to some species (Clarke 1974a). In walleye, free carbon dioxide concentrations of 30 - 40 mg/L caused a complete extinction of the light avoidance response (Scherer 1971). Fish may avoid free carbon dioxide levels as low as 1.0 to 6.0 mg/L (Brinley 1943, Hoglund 1961). The presence of low levels of free carbon dioxide in most waters and the ability of fish to detect these levels, along with the ability of fish to acclimatize to higher levels if necessary, probably prevent this constituent from being a real hazard (Duodoroff & Shumway 1970).

7.3 Chloride

Chloride occurs in natural watercourses in low concentrations. Sources can include the atmosphere, land runoff and sub-surface salt deposits. Municipal sewage treatment plant discharges contribute substantial amounts of chloride as do a wide variety of industries. Runoff of salt from winter roadway deicing operations can, in the vicinity of highly populated areas, increase chloride levels in nearby water bodies during the months December through March. Generally, in rivers, levels decrease during the spring, summer and autumn. Chloride levels in the lower Great Lakes do not fluctuate substantially on a seasonal basis but have, over the past seven or eight decades, approximately tripled to a level today of about 29 milligrams per litre in Lake Ontario and 19 mg/L in Lake Erie. Chloride levels in the Grand River downstream from the major municipalities of Kitchener, Waterloo, Cambridge and Guelph, average approximately 50 to 60 mg/L during the winter and 40 to 50 mg/L during the summer (J. Ralston, Personal Communication).

Chloride concentration in water is similar to total salinity which affects osmosis in fish (Clarke 1974a). McKee and Wolf (1971) report lethal chloride concentrations to trout as low as 400 mg/L, while some other species survived 2000 mg/L.

7.4 Chlorine

Elemental chlorine is highly soluble in water, reacting readily with animal and plant tissues (EPA 1976). As a result of the denaturing effect on tissues, chlorine is used as a disinfectant in a variety of effluents from sewage treatment plants, power plants, textile and paper mills. Free chlorine rapidly combines with nitrogenous compounds to form chloramines. The chlorine demand of waste water is usually sufficient to use up almost all free chlorine. Therefore, chlorine toxicity to aquatic organisms relates to total residual chlorine which is free chlorine plus chloramines (EPA 1976). Residual chlorine concentrations of 0.5 - 2.0 mg/L are maintained in many waste water treatment plants (IJC 1978), or are intermittently used for antifouling in condenser cooling of heat exchange systems. These concentrations are well below any levels known to demonstrate physiological effects on mammals (Brungs 1973).

IJC (1978) and MOE (1978) recommend that total residual chlorine (TRC), as measured by the amperometric (or equivalent method) should not exceed 0.002 mg/L to protect aquatic life. EPA (1976) recommend criteria for total residual chlorine of 0.002 mg/L for salmonids and 0.01 mg/L for other freshwater organisms. Thurston *et al.* (1979) criticize the EPA (1976) criteria and recommend in their place a single criterion of 0.003 - 0.005 mg/L based on the amperometric titration in conjunction with a polarograph. The ortho-tolidine method commonly used for chlorine determinations is biased on the low side and therefore, is inadequate for total residual chlorine determinations in waste waters or receiving streams (IJC 1978).

To determine the effects of residual chlorine from sewage plant wastes, many caged fish studies have been conducted. Immediately below chlorinated effluents, fish species diversity and abundance is usually low with the species diversity index reaching zero in water with a total residual chlorine level of 0.25 mg/L and no fish present above 0.37 mg/L (Tsai 1973). Further downstream feeding and spawning movements may be affected, especially when the effluent extends across the river, and fish cannot avoid it (Clarke *et al.* 1977). For short term exposure (i.e. intermittent treatments from power plants), NAS/NAE 1973 recommends that total residual chlorine concentrations should not exceed 0.05 mg/L for a period of 30 minutes in any 24 h period. For intermittent disinfecting Brungs (1973) recommends that concentrations should not exceed 0.01 mg/L for more than 30 minutes in a day to protect trout and salmon. Table 7.4 lists some effects of chlorine on fish.

Table 7.4. Responses of fish to various concentrations of total residual chlorine (TRC).

Species	TRC mg/L	Fish Response	Reference
Brooktrout	0.083	7 day LC_{50}	McKim *et al.* (1978)
	> 0.02	Not found	Tsai (1973)
Rainbow trout	0.19	96 h LC_{50}	Clarke *et al.* (1977)
	0.014 - 0.029	96 h LC_{50}	Mich. DNR (1971)
Brown trout	0.02 - 0.18	30 min. exposure LC_{50}	Basch & Truchan (1976)
	0.01	45.5 h LC_{50} (available chlorine)	Clarke (1974)
Smallmouth bass	0.5	15 h LC_{50}	Pule (1960)
Largemouth bass	0.36	12 h LC_{50}	Arthur (1972)
	0.26	7 day LC_{50}	McKim *et al.* (1978)
Walleye	0.15	7 day LC_{50}	McKim *et al.* (1978)

7.5 Detergents

A detergent is a natural or synthetic substance which will remove dirt or soil and keep it suspended in water (Thompson 1974). Various detergents are found in sewage and industrial effluents with the largest amounts coming from household cleaning agents (NAS/NAE 1973). In 1965, the detergent industry shifted from tetrapropylene derived alkylbenzene sulfonates (ABS) to the more biodegradable linear alkylate sulfonates (LAS), which are initially 2 to 4 times more toxic than ABS but whose toxicity disappears with biodegradation (NAS/NAE 1973).

From a review of the toxic effects of LAS detergents, EPA recommends that concentrations in the receiving water should not exceed 0.05 of the 96 h LC_{50} of the most sensitive species: at any time or place, LAS concentrations should not exceed 0.2 mg/L, (NAS/NAE 1973). MOE (undated) recommends that concentrations should not exceed 1/7 of 48 h LC_{50} at any time or place for LAS or ABS. The toxicity of these two synthetic detergents on fish has been tabulated by Thompson (1974), and summarized in Table 7.5.

Table 7.5. Responses of fish to synthetic detergents.

Conc. mg/L	Fish Response	Reference
ABS (Tetrapropylene - derived Alkylbenzene Sulfonate)		
Bluegill		
17.4	96 h LC_{50} (soft water,18°C DO 5-9 mg/L)	Patrick & Cairns (1968)
8.2	96 h LC_{50} (Hardness 50 mg/L $CaCO_3$, 23°C)	Thatcher (1968)
Rainbow Trout		
10.8	96 h LC_{50} (hardness 300mg/L $CaCO_3$,15°C)	Calamari & Marchetti (1973)
LAS (Linear alkylate sulfonates)		
Bluegill		
4.6	0% of embryos hatched	Hokansen &Smith (1971)
3.7	88% of embryos hatched	Hokansen & Smith (1971)
3.0	96 h LC_{50} (Compound of C_{12} - LAS)	Swisher *et al.* (1964)
0.64	96 h LC_{50} (Compound of C_{14} - LAS)	Swisher *et al.* (1964)
Rainbow Trout		
1.7	96 h LC_{50} (hardness 300 mg/L $CaCO_3$, 15°C)	Calamari & Marchetti (1973)
Soap and Other Detergents		
Rainbow Trout		
4.7	96 h LC_{50}, non-ionic detergent -nonylphenol ethoxylate (hardness 300 mg/L $CaCO_3$, 15°C)	Calamari & Marchetti (1973)
Fathead Minnow		
920 - 1,800	96 h LC_{50} household soaps(hard water, hardness 400 mg/L $CaCO_3$)	Henderson *et al.* (1959)
29 - 42	96 h LC_{50} household soaps (sort water, hardness 20 mg/L $CaCO_3$)	Henderson *et al.*(1959)

7.6 Dissolved Gas Supersaturation

Total dissolved gas (TDG) supersaturation may result from several situations, (EPA 1976; Thurston *et al.* 1979):

(i) Excessive algal photosynthesis increases dissolved oxygen concentrations above saturation levels. Increased water temperatures aggravate gas supersaturation problems by not only encouraging algal blooms but also decreasing gas solubilities in water.

(ii) Water discharging over dams, entrains air which is driven into solution under increased hydrostatic pressure when the water enters the pool below the dam. This situation may also occur under natural waterfalls.

(iii) While passing through heat exchangers, cooling waters may become supersaturated.

(iv) Air used in turbine intakes to reduce cavitation may no into solution.

(v) Improper engineering of hatchery water supplies may create venturi action which can increase dissolved gas levels above saturation.

Emboli or gas bubbles can form in tissues of fish exposed to excessive dissolved gas pressure. This occurs when dissolved gases in the circulatory system come out of solution resulting in what is commonly referred to as "gas bubble disease". Fish may die when emboli block capillaries (EPA 1976) or interfere with their negative or neutral buoyancy (Fickeisen & Montgomery 1978). Hydrostatic pressure, which tends to keep gases in solution, increases with depth. Therefore, gas bubbles are more likely to occur in shallow waters making littoral zone fish species more susceptible to this disease.

The EPA (1976) criterion and the MOE (1978) objective states that "To protect life, the dissolved gas concentration should not exceed 110% of the saturation value for gasses at the existing atmospheric and hydrostatic pressures".

At 125% TDG, Boucke *et al.* (undated) determined LC_{20}'s for salmonid adults, smolts and parr of 18, 17 and 24 hours respectively, while at 120% TDG values were 48, 41 and 53 hours. They also showed that a 3 month exposure of 110% TDG did not interfere with the success of fertilization and hatching in chinook salmon. For cutthroat trout, Fickeisen and Montgomery (1978) determined an LC_{50} for 120% TDG of 34 hours.

7.7 Mirex (Dechlorane)

This compound has been used in insecticides in the southern United States for fire ant control. Mirex was also used in the Great Lakes Basin as a flame retardant called Dechlorane. The compound is very stable and is extremely resistant to biological and chemical degradation. Mirex accumulates in the food chain and its toxic effects on some aquatic organisms are cumulative and delayed (IJC 1978).

The EPA (1976) criterion and MOE (1978) objective for mirex is 0.001 µg/L. The MOE states that, because of the properties of mirex (ie. persistent, bioaccumulative), any release of this substance should be completely eliminated. It recognizes however, the presence of this chemical in the environment as the result of past losses and offers a 0.001 µg/L objective as guidance for evaluating the impact of mirex on aquatic biota. IJC (1978) recommends that mirex, including its degradation products, should be substantially absent (i.e. at less than detection levels as determined by the best available scientific methodology) from water and aquatic organisms. Presently detection levels are 0.005 µg/L for water and 0.005 µg/g for biological tissues (IJC 1978). Since mirex concentrations below the detection limit in water may result in detectable levels in tissues, IJC (1978) recommends an emphasis on tissues for surveillance purposes.

7.8 Nitrate and Nitrite

Nitrogen enters water bodies from point sources such as municipal and industrial wastes, septic tanks and feedlot discharges. Nonpoint nitrogen sources include, farm-site fertilization, animal wastes, lawn fertilization, leaching from waste disposal dumps or sanitary landfills, and atmospheric fallout (from many combustion sources) and the natural mineralization of organic soil (EPA 1976).

Nitrite (NO_2-N)

Ammonia is converted to nitrite which is then converted to nitrate in the nitrification process. Since the first conversion is rate-limiting, nitrite is generally only present in trace amounts in freshwater systems. If the stability of this process is disrupted (i.e. a malfunction at a sewage treatment plant, or extremely low ambient temperatures), then nitrite may increase to toxic levels (Russo and Thurston 1977). Nitrite oxidizes hemoglobin to methemoglobin thereby reducing the oxygen carrying capacity of blood. Russo and Thurston (1977) and Thurston *et al.* (1978) conclude that 0.06 mg/L nitrite nitrogen (NO_2-N) would protect salmonids. Other toxicity data from the former paper above is presented in Table 7.8.

Nitrate (NO_3-N)

Nitrate is considerably less toxic to fish than nitrite. In mammals nitrate is reduced to nitrite in the gut. To protect bottle-fed infants the EPA (1976) criterion for nitrate in public water supplies is 10 mg/L which is well below levels considered toxic to fish (see Table 7.8).

Table 7.8. Responses of fish to various concentrations of nitrite (NO_2-N) and nitrate (NO_3-N).

Nitrite (NO_2-N) mg/L	Fish Response	Reference
Rainbow Trout		
0.19-0.27	96 h LC_{50}	Russo *et al.* (1974)
Chinook Salmon		
2.9	96 h LC_{50}	Westin (1974)
Channel Catfish		
13	96 h LC_{50}	Colt & Tchobanoglous (1976)

Nitrate (NO_3-N) mg/L		
Rainbow Trout		
6,000	96 h LC_{50}	Westin (1974)
Chinook Salmon		
5800	96 h LC_{50}	Westin (1974)
<25	best growth	Westin (1974)

7.9 Phenols

Phenolic compounds are defined as hydroxy derivatives of benzene and include a wide variety of organic chemicals. They arise from the distillation of coal and wood, oil refineries, chemical plants, domestic sewage, and the microbial degradation of pesticides. Phenols can be directly toxic to fish by lowering the amount of available oxygen (EPA 1976) and also by adversely affecting their gills, nervous system, liver, spleen and cardiovascular system (Klaverkamp *et al.* 1977).

EPA (1976) and MOE (1978) recommend that phenol concentrations not exceed 1.0 µg/L to protect against fish flesh tainting. Thurston *et al.* (1979) accept this level for chlorophenols, but strongly criticize the EPA criterion as not justified for non-chlorinated phenolics regarding fish flesh tainting, and too stringent for any phenolic for protection of aquatic biota. They also suggest that separate criteria be developed for different phenolic classes. Chlorinated phenolics are more acutely toxic, and have approximately a 1000 fold greater bioaccumulation potential in fish than other phenolics (Thurston *et al.* 1979). EIFAC (1973) recommends that the concentration of phenol, cresols, or xylenols should not exceed 1000 µg/L either singly or collectively (500 µg/L when 2,5 - xylenol is the main phenolic constituent) to protect salmonids. Thurston *et al.* (1979) suggest that this is suitable for monohydric phenols but that a lower criterion is necessary for chlorophenols.

7.10 Phosphate Phosphorus

Phosphate phosphorus has no direct relationship to fish toxicity, but available phosphorus stimulates algal growth if it is the growth limiting element. Excessive algal growth contributes to aesthetic deterioration and increased oxygen demand from plant decomposition.

MOE (1978) recommends the following guidelines for total phosphorus, which should be supplemented by site-specific studies.

30 µg/L - Excessive plant growth in rivers and streams should be eliminated.

20 µg/L - During ice-free period should prevent nuisance concentrations of algae in lakes.

10 µg/L - During ice-free period should provide a high level of protection against aesthetic deterioration. This should apply to all lakes naturally below this value.

Thurston *et al.* (1979) criticize an approach such as presented above as simplistic, preferring to base criteria on total phosphorus loadings ($g/m^2/yr$) and mean depth and hydraulic residence times of water bodies (Table 7.10).

Table 7.10. Permissible and critical total phosphorus loadings (from Thurston *et al.* 1979).

Mean Depth/Hydraulic Residence Time (m/yr)	Oligotrophic or Permissible Loading (g/m /yr)	Eutrophic or Critical Loading ($g/m^2/yr$)
0.25	0.102	0.205
0.5	0.105	0.21
1.0	0.11	0.22
2.5	0.125	0.25
5.0	0.15	0.30
7.5	0.175	0.35
10.0	0.20	0.40
25.0	0.35	0.70
50.0	0.60	1.2
75.0	0.85	1.7
100.0	1.1	2.2

Based on relationships developed by Vollenweider (1976).

7.11 Polychlorinated Biphenyls (PCB)

PCBs are a group of chlorinated organic compounds developed in the 1920's. These chemicals are not formed in the natural environment so their presence in fish can always be attributed to man's activities. PCBs are very stable; that is, they do not easily break-down chemically or naturally and they burn only at extremely high temperatures. These properties led to widespread use of PCBs in transformer fluids, hydraulic fluids, oils, greases, and as fire retardants and plasticizers in products such as paints, inks and adhesives. Until the environmental and health hazards of PCB were discovered, there were no special precautions taken to prevent losses to the environment. Today the use and disposal of PCBs or PCB-contaminated equipment is very closely regulated. Recently the production of PCBs was terminated by the only North American manufacturer.

Fish readily bioaccumulative PCB's in their tissues by factors of 1.0×10^6 to 2.0×10^7 over water concentrations (Thurston *et al.* 1979). Fish with PCB residues of 2 µg/g fed to ranch mink precluded survival of their offspring (Ringer *et al.* 1972) while reproduction was nearly eliminated in ranch mink fed a beef diet with 0.64 µg/g PCB (Platonow & Karstad 1973).

Because of the high bioaccumulation factors of PCB's in fish and their subsequent effects on higher predators, IJC (1977) recommends that the concentration of total PCB's in fish tissue (on a wet weight basis) should not exceed 0.1 µg/g. Both IJC (1977) and Thurston *et al.* (1979) recommend the tissue criterion for surveillance since the extremely low values recommended for PCB concentration in water are beyond routine analytical sensitivities. The MOE recommends that, because of the persistent and bioaccumultive properties of PCB, any release of this substance should be completely eliminated. In recognizing the presence of this compound in the environment as the result of past losses and considering the possibility of accidental spills, the MOE provides an objective of 0.001 µg/L intended as guidance for evaluating the impact of PCB on aquatic life (MOE, 1978).

7.12 Sulfide (Hydrogen Sulfide)

Hydrogen sulfide is a flammable, poisonous gas soluble in water to 4000 mg/L at 20°C (IJC 1978). It results from decomposition of natural detritus and organic benthic deposits, discharges of anaerobic sewage, and sulfide wastes from tanning, pulp and paper, textile, chemical, and gas manufacturing industries (IJC 1978). Under aerobic conditions hydrogen sulfide is rapidly oxidized to form sulphates. Hydrogen sulfide may reach toxic concentrations near the sediment-water interface if organic material is undergoing anaerobic decomposition (IJC 1978). Undissociated hydrogen sulfide is the toxic form (Thurston *et al.* 1979) with the degree of dissociation dependent on pH. At pH 9 only about 1% of the hydrogen sulfide is undissociated, while at pH 6.5 about 75% is in the toxic undissociated form. The toxicity of hydrogen sulfide to fish increases with increased temperature and reduced dissolved oxygen concentrations (Thurston *et al.* 1979).

The EPA (1976) criteria of 0.002 mg/L undissociated hydrogen sulfide is also recommended by IJC (1978) and MOE (1978) to protect aquatic life. Table 7.12 documents some effects of hydrogen sulfide on fish and also lists some no-effect levels compiled by Smith and Oseid (1973).

Table 7.12. Responses of fish to various concentrations of hydrogen sulfide (H_2S).

H_2S mg/L	Fish Response	Reference
0.1 - 0.02	Walleye eggs do not hatch	Colby & Smith (1967)
0.05	96 h LC_{50} - walleye fry	Colby & Smith (1967)
0.037	96 h LC_{50} - northern pike eggs	Adelman & Smith (1970)
0.026	96 h LC_{50} - northern pike sac fry	Adelman & Smith (1970)
0.017	96 h LC_{50} - juvenile brook trout	Smith & Oseid (1973)
0.0014	46 days - bluegill egg deposition reduced	Kimball (1978)

No-effect levels of H_2S (mg/L)
(Source; Smith and Oseid 1973)

Species	Spawning	Juvenile Growth	Fry	Hatch
Brooktrout	<0.005	<0.0015	<0.026	<0.005
Rainbow trout				<0.006
Northern pike			0.004	
Fathead minnow	0.0013	0.003		0.005
Goldfish	0.005	<0.007	0.014	<0.007
Walleye		0.004	<0.009	<0.012
Bluegill	0.007	0.002	<0.008	<0.011

8. TOXICOLOGICAL RELATIONSHIPS AMONG PARAMETERS

8.1 Introduction

Consideration of the toxicological relationships among parameters is extremely vital since fish in any natural system continuously experience a large array of parameters. Interactions of parameters may result in effects on fish that are antagonistic, or additive either more-than, less-than, or exactly additive (Sprague 1970). Little is known about the effects of the vast majority or the near limitless combinations of pollutants, although in some cases results are well documented. Some of these data appear in the sections on individual parameters. Table 8.1 provides a brief summary for pairs of parameters compiled from sections 8.2 - 8.18. References cited in Table 8.l and sections 8.2 - 8.18 are often from review papers containing in some cases several citations from original authors. Again, because of the complexity of this topic, this section can only provide limited guidance concerning interactions among parameters.

Table 8.1. Interactions between parameters; "+" indicates toxicity of parameter 'A' increases with increased levels of parameter 'B'; "-" indicates toxicity of parameter 'A' increases with decreased levels of parameter 'B'. References (in brackets) are listed on next page.

	Parameter 'B'																
Parameter 'A'	NH_3	Cd	Cl_2	Cr	Cu	HCN^-	hd.*	H_2S	Pb	Ni	NO_2-N	O_2	pH	Pest.	pls	T.	Zn
Ammonia (HN_3)												-(11)	+(4,6,13)		+(17)		
Cadmium (Cd)					+(20)		-(6)										+(20)
Chlorine (Cl_2)												-(7)	-(2)		+(9)		
Chromium (Cr)							-(6)										
Copper (Cu)							-(1,14)	-(17)		+(6)		-(8)	+(4)				+(5)
Cyanide (HCN^-)												-(8)	-(5)			+(11)	
Hydrogen Sulfide (H_2S)												-(12,18)				+(10,12)	
Lead (Pb)												-(12)	-(12)			+(12)	
Nickel (Ni)						+(6)						-(8)					
Nitrite (NO_2-N)			-(15)														
Oxygen (O_2)																	
pH																	
Pesticides (Pest.)		+(20)			+(20)				+(20)							+(3,16, 19)	
Phenols (pls)					+(6)							-(8)					+(20)
Temperature (T.)																	+(5)
Zinc (Zn)		+(6)										-(6)					

* Hardness

REFERENCES FOR TABLE 8.1

1. Anon. (1976)
2. Brungs (1973)
3. Brungs *et al.* (1978)
4. Bulkley (1975)
5. Cairns *et al.* (1975)
6. Clarke (1974a)
7. Clarke *et al.* (1977)
8. Davis (1975a)
9. EIFAC (1974)
10. EPA (1976)
11. Hunka (1974)
12. IJC (1978)
13. Lloyd (1961)
14. Pickering and Henderson (1966)
15. Russo and Thurston (1977)
16. Simonin and Skea (1977)
17. Smith (1974)
18. Smith and Oseid (1973)
19. Sprague (1970)
20. Thompson (1974)

8.2 Ammonia

1. pH - ammonia toxicity increases as pH increases above 7.0 (Bulkley 1975; Clarke 1974a).

2. Incipient LC_{50}'s for trout (Ammonia as N mg/L)

pH	bicarbonate alkalinities mg/L				
	25	50	100	200	400
6.5	370	340	340	≥ 340	≥340
7.0	175	140	125	110	110
7.5	100	70	53	42	37
8.0	72	45	30	21	16
8.5			23	13	9

* Values approximate, derived from Figure 3, Lloyd (1961).

3. Oxygen - ammonia toxicity increases as oxygen decreases (IJC 1977).

4. Temperature - ammonia toxicity increases as temperature increases (see Table 7.1a, Section 7).

5. Phenols - increase adverse effects of ammonia (Smith 1974).

8.3 Cadmium

1. Toxicity is more-than-additive when cadmium is mixed with copper, and/or zinc (Thompson 1974).

2. Hardness - cadmium toxicity increases as hardness decreases (Clarke 1974a).

8.4 Chlorine

1. pH - residual chlorine is more toxic at a pH of 6.3 versus 7.0, because more free chlorine is present at lower pH (Brungs 1973).

2. Oxygen - chlorine toxicity to rainbow trout increases as oxygen decreases (Clarke *et al.* 1977).

3. Phenols - when mixed with concentrations of chlorine as low as 0.001 mg/L, they are likely to produce tainted fish flesh (EIFAC 1974).

8.5 Chromium

1. Hardness - chromium toxicity increases as hardness decreases (Clarke 1974a)

	Hardness ($CaCO_3$ mg/L)	96 h LC_{50} mg/L
Bluegill	20	118
	360	133
Fathead minnow	20	17.6
	360	27.3

8.6 Copper

1. Hardness - copper toxicity increases as hardness decreases

Copper µg/L	Hardness $CaCO_3$ mg/L	Response	Reference
10,200	360	Bluegill 96 h LC_{50}	Pickering & Henderson(1966)
660	20	Bluegill 96 h LC_{50}	Pickering & Henderson(1966)

In hard water (200 mg/L $CaCO_3$), 2 mg/L copper sulphate can be safely used as an aquatic herbicide however, in soft water (20 mg/L $CaCO_3$) copper sulphate concentrations as low as 0.02 mg/L may kill fish (Anon. 1976).

2. pH - copper toxicity increases as pH increases (Bulkley 1975).

3. Oxygen - copper toxicity increases markedly at oxygen concentrations below 5.8 mg/L (Davis 1975a).

4. LAS detergent - and copper mixtures are more toxic to rainbow trout than as individual toxicants (Thompson 1974).

5. Nickel and zinc - when mixed with copper have additive effects (Clarke 1974a).

6. Hydrogen sulfide - the resistance of bluegill to copper increases at sublethal concentrations of hydrogen sulfide (Smith 1974).

8.7 Cyanide

1. Temperature - cyanide toxicity increases with increased temperatures (Hunka 1974).

2. pH - cyanide toxicity increases with decreased pH (Cairns *et al.* 1975).
   - range of 6.0 - 8.5 pH, may not affect the toxicity of cyanide (Smith 1974).

3. Oxygen - cyanide toxicity increases with reduced oxygen (Davis 1975a) (i.e. trout exposed to 0.105 mg/L cyanide at 17°C survived 8 h at 9.5 mg/L oxygen buy only 10 minutes at 4.0 mg/L oxygen) (Smith 1974).

4. Hardness - apparently no affect on cyanide toxicity (Sprague 1970).

8.8 Hardness

1. Fluoride - toxicity increases with decreased hardness (Smith 1974).

8.9 Hydrogen Sulfide

1. Toxicity increases as pH and oxygen decrease and temperature increases (IJC 1978).

Walleye eggs	(at temperature of 14°C)	(Smith & Oseid 1973)
H_2S mg/L	Oxygen mg/L	% Hatch
0.013	3	62
0.012	6	86
0.039	3	21
0.037	6	77

2. Goldfish and fathead minnow are more tolerant to H_2S as temperature drops to 6 - 10°C (EPA 1976).

8.10 Lead

1. Hardness - lead toxicity increases with decreased hardness (see criteria, section 5.6).

2. Oxygen - lead toxicity increases markedly at concentrations below 5.8 mg/L (Davis 1975a).

8.11 Nickel

l. Cyanide - mixed with nickel produces more-than-additive effect (Clarke 1974a).

8.12 Nitrite

1. Chloride - has an antagonistic effect on nitrite toxicity (Russo and Thurston 1977):

Rainbow trout (at 10°C and pH 7.7 - 7.9)
96 h LC_{50}

Nitrite mg/L	Chloride ion mg/L
0.46	1.2
3.54	10.4
12.2	49.9

8.13 Oxygen

Several pollutants increase in their toxicity at reduced oxygen levels, because the respiration rate increases and this raises the toxicant level on the gill surface (Clarke 1974a).

8.14 pH

1. Nickel - cyanide complexes - are tolerated 1000 times more within a pH range of 6.5 - 8.0 than outside this pH range (Huet 1962).

8.15 Pesticides

1. Temperature - Pyrethrin toxicity increases as temperature rises (Brungs *et al.* 1978).
   - Salmon are more susceptible to DDT at lower temperatures (Sprague 1970).
   - Endrin is more toxic below 20°C (Sprague 1970).

2. LAS detergent mixed with sublethal concentrations of parathion produces more-than-additive toxic response to fathead minnow (Thompson 1974).

3. Heavy metals mixed with insecticides produce more-than-additive effects (Thompson 1974).

4. Cutrine (algicide) and Diquat (herbicide) separately killed 30% and 5% of fish at concentrations of 0.162 mg/L and 5.5 mg/L respectively, but when they were mixed at the same concentrations, fish mortality was 100% (Simonin & Skea 1977).

8.16 Phenols

1. Oxygen - phenol toxicity increases markedly at oxygen concentrations below 5.8 mg/L (Davis 1975a).

2. Copper and/or zinc - mixed with phenol produces additive effects (Clarke 1974a).

3. Temperature - rises in some experiments have decreased toxicity of phenol and increased it in other experiments (Smith 1974).
   - Long term tests show that phenols are more toxic at 6°C than at 18°C (Sprague 1970).

4. pH - does not appear to alter the toxicity of phenol to rainbow trout or carp (Smith 1974).

5. Hardness - phenol toxicity is slightly lower in hard water; some other works say that hardness has no effect (Smith 1974).

8.17 Temperature

Sprague (1970) states that no assumption should be made about temperature effects on toxicity, owing to the complexity and variable nature of temperature-toxicity relationships. However, Clarke (1974a) found that several works reported fish survive toxicant exposure longer at lower temperatures, and says that this is possibly due to the oxygen content being greater at lower temperatures. Therefore, past experiments relating to temperature effects on toxicants should be viewed with caution, especially if the dissolved oxygen was not recorded.

8.18 Zinc

1. Cadmium - mixed with zinc produces additive effects (Clarke 1974a).

2. Copper or nickel - when mixed with zinc are more-than-additive (Clarke 1974a).

3. Temperature -
   - at a lethal zinc concentration of 32 mg/L, blue-gills died 2.6 times faster at 30°C than at 20°C (Burton *et al.* 1972).
   - rainbow trout: zinc toxicity increased by a factor of 2.4 when temperature was raised from 12 to 22°C (Burton *et al.* 1972).
   - other experimenters found temperature had no effect on the toxicity of sublethal zinc concentrations for bluegill and rainbow trout (Sprague 1970).

4. Oxygen - when rainbow trout were acclimated at 17°C and pH 7.8, they became more sensitive to zinc as O_2 decreased from 8.9 to 3.8 mg/L (Clarke 1974a).

9. SUMMARY

The following tables provide a brief overview of data previously presented in this report. These table do not contain all the data and background material from each section and therefore, the reader is strongly advised to consult the individual sections.

Table 9.1. Summary of sublethal and lethal dissolved oxygen concentrations, and thermal maxima for sport fishes.

Species	Life Stage[2]	Dissolved Oxygen (mg/L)			Temperature (°C)			
		Sublethal[3]	Lethal[4]	UIL[5]	Growth Season		Reproductive Season	
					MWAT[6]	24h Max.	MWAT[6]	24h Max.
Brook trout	E		2.5					
	A	9.1	3.4	25.5	19	24	9	13
Rainbow trout	A	8.7	2.5	26.5	19	24	9	13
Brown trout	A	4.6	1.8	23.5	17	24	8	15
Smallmouth bass	A		1.3	32.0	29	--	17	23
Largemouth bass	E	6.0	2.8					
	A	6.0	0.8	36.4	32	34	21	27
Northern pike	E		3.1					
	A	4.0	0.8	33.5	28	30	11	19
Walleye	E		4.6					
	A	1.5		31.6	25	--	8	17

1 5ee text Section 2.
2 E = eggs, embryos, or larvae; A = juveniles or adults
3 highest concentration reported in Section 2 causing a decrease in some physiological parameter (i.e. growth, O_2 uptake, swimming speed).
4 highest concentration reported in Section 2 resulting in deaths of some individuals.
5 UIL = upper incipient lethal temperature
6 MWAT = maximum weekly average temperature (NAS/NAE 1973)

Table 9.2. Summary of general dissolved oxygen criteria (Davis 1975b) and objectives (MOE 1978) for sport fishes.

Temperature °C	Minimum Dissolved Oxygen Concentration (mg/L)			
	Cold-Water Fish		Warm-Water Fish	
	MOE (1978)	Davis (1975b)[1]	MOE (1978)	Davis (1975b)[2]
0	8	14.3	7	8.8
5	7	12.5	6	7.7
10	6	11.1	5	6.8
15	6	9.9	5	6.1
20	5	9.2	4	5.5
25	5	8.4	4	5.5

[1] for high level of protection for salmonid eggs and larvae.

[2] for high level of protection

Table 9.3. Summary of criteria for the protection of aquatic life for solids (suspended, settleable), turbidity, and pH.

Solids (suspended, settleable)
Criteria (EIFAC 1965):

Max. Conc. of Susp. Solids mg/L	Level of Protection to Fisheries
< 25	High - no harmful effects on fisheries
80	Moderate - good fisheries but possible reduced yield
400	Low - unlikely to support good fisheries
>400	Very low - only poor fisheries

Turbidity

Criteria (IJC 1978):

Additions of suspended matter should neither alter the natural Secchi disk reading by more than 10% (MOE 1978), nor settle to form objectionable deposits (IJC 1978).

pH

Criteria (NAS/NAE 1973):

pH	Max. Fluctuation Outside Normal Seasonal Range	Level of Protection
6.5-8.5	0.5	Nearly maximum
6.0-9.0	0.5	High
6.0-9.0	1.0	Moderate
5.5-9.5	1.5	Low

Table 9.4. Summary of safe and lethal metal concentrations for fish, and criteria for the protection of aquatic life (concentrations in mg/L).

		Safe Concentration	Lethal Concentration	Criteria
Aluminum				
Rainbow trout			5.0	
Arsenic		0.7 - 7.0		0.051
Brooktrout			18.0	
Muskellunge (swim-up fry)			0.05	
Cadmium				0.00021 0.0004 - 0.015 [2]
Brook trout		0.001 - 0.D12	0.012 - 0.045	
Rainbow trout		0.0007 - 0.021	0.003 - 0.040	
Brown trout		0.0011 - 0.0117		
Smallmouth bass		0.0043 - 0.0127		
Bluegill		0.031 - 0.080		
Chromium				0.1 [1, 3]; 0.05 [4]
Brook trout	(soft water)	0.2	5.9	
Rainbow trout	(soft water)	0.2	69.0	
Bluegill	(soft water)		118.0	
	(hard water)		133.0	
Copper				
Brook trout		0.01*	0.1	
Rainbow trout	(soft water)		0.064	
	(hard water)		0.27	
Bluegill			0.74	
Iron				1.0 [1]; 0.3 [3, 5]
Brook trout		7.5 - 12.5		
Northern pike			1.0 - 2.0	
Lead				0.005 - 0.025 [3, 6]
Brook trout	(soft water)	0.058 - 0.119	4.1	0.004 - 0.1 [2]
Rainbow trout	(soft water)	0.004 - 0.146	1.2	
	(hard water)	0.12 - 0.36	471.0	
Bluegill	(soft water)	0.07 - 0.1		
Mercury				0.0002 [3, 6] in fish - 0.0005 mg/g [3,6] 0.000051
Brook trout			0.003	
Nickel				0.025 [3, 5]
Bluegill	(soft water)	0.053**	5.27	
	(hard water)	0.396**	39.6	
Carp	(soft water)	0.106**	10.6	
Pumpkinseed	(soft water)	0.081**	8.1	
Zinc				0.03 [3, 6] 0.05 - 0.6 [2]
Brook trout	(soft water)	0.014 - 0.025**	1.38 - 2.5	
Rainbow trout	(soft water)	0.004**	0.43	
	(hard water)	0.072**	7.21	
Bluegill	(soft water)	0.054 - 0.106**	5.4 - 10.6	
	(hard water)	0.409**	40.9	

* calculated as 0.1 X 96 h LC_{50} (EPA 1976)

** calculated as 0.01 X 96 h LC_{50} (EPA 1976)

1 EPA (1976)

2 Thurston *et. al.* (1979)

3 MOE (1978)

4 NAS/NAE (1973)

5 IJC (1978)

6 IJC (1977)

Table 9.5 Summary of safe and lethal of other substances to fish and criteria for the protection of aquatic (Concentrations in mg/L).

	Safe Concentration	Lethal Concentration	Criteria
Ammonia			0.02 [1,2,3]
Brook trout		2.5	
Rainbow trout		0.4 - 0.58	
Bluegill		6.0 - 7.4	
Perch	0.015*	0.29	
Carbon dioxide			
Trout (Species not given)		45.0	
Chloride			
Trout (Species Not Given)		400.0	
Chlorine			0.002 [2, 3] 0.003 - 0.005 [4]
Brook trout		0.083	
Rainbow trout		0.014 - 0.19	
Brown trout		0.01 - 0.02	
Smallmouth bass		0.5	
Largemouth bass		0.26 - 0.36	
Walleye		0.15	
Detergents (see text)			
Dissolved gas supersaturation	(see text)		
Mirex			0.000001 [1,2] in fish 0.000005 mg/g [3]
Nitrite	0.06		
Rainbow trout		0.19 - 0.27	
Chinook salmon		2.9	
Nitrate			
Rainbow trout		6000	
Chinook salmon		5800	
PCB's			0.000001 [1, 2] in fish 0.0001 mg/g [4]
phenols			0.001 [1, 2]
Phosphate phosphorus (see text)			1.0 [5]
Sulfide (hydrogen sulfide)			0.002 [1, 2, ,3]
Brook trout	0.0015	0.017	
Rainbow trout	0.006		
Northern pike	0.004	0.076	
Bluegill	0.002		
Walleye	0.004	0.05	

* calculated ac 0.05 x 96 h LC_{50} (EPA 1976)

1 EPA (1976)
2 MOE. (1978)
3 IJC (1970)
4 Thurston *et al.* (1979)
5 EIFAC (1973)

10. GLOSSARY

Acutely toxic - Causing death or severe damage to an organism by poisoning during a brief exposure period, normally 96 hours or less, although there is no clear line of demarcation between acute and chronic toxicity (EPA 1976).

Additive - Toxicity of two or more components increase in an additive fashion: example; two toxicants are exactly additive when ½ the concentration of A and ½ the concentration of B together produce the same response as either A concentration or B concentration.

Ambient - Surrounding levels, the levels which normally exist.

Antagonistic - Two or more components act to reduce the toxicity to a level lower than that of each individual component (Sprague 1970).

Bioaccumulation - The uptake and retention of environmental substances by an organism from its environment as opposed to uptake from the food (NAS/NAE 1973).

Biomagnification - The uptake and retention of environmental substances by an organism from its food.

Chronically Toxic - Causing death or damage to an organism by poisoning during prolonged exposure (may range from several days to weeks, months or years) (EPA 1976).

Incipient - Just beginning, in an initial stage.

Incipient Lethal Level (ILL) - That level of the lethal identity beyond which the organism can no longer survive for an indefinite period of time.

LC_{50} - The lethal concentration of toxicant for 50% of the individuals tested. A time period must always be specified (i.e. 96 h LC_{50}).

Mixing Zone - An area contiguous to a point source, where exceptions to water quality objectives and conditions otherwise applicable to the receiving water body may be granted (IJC 1977).

More-than-Additive - Toxicity of two or more components increase in more-than-additive fashion (often termed synergistic effect). example; ½ the concentration of A and ½ of concentration of B together produce a toxic response greater than either A concentration or B concentration (Sprague 1970).

Receiving Water - The body of water that is receiving the polluted effluent. The major factor affecting the toxicity of effluent is the dilution by the receiving water (i.e. relative volume of effluent and receiving water).

Residual - Remaining, not eliminated.

mg/L (Milligram per litre) - The concentration at which 1 thousandth of a gram is contained in a volume of 1 litre.

µg/L (Microgram per litre) - The concentration at which 1 millionth of a gram is contained in a volume of 1 litre.

Appendix 1. List of contacts and persons that assisted in the literature search.

Name	Affiliation	Specialization
Dr. John Allin	Ministry of Natural Resources Fisheries Branch Queen's Park Toronto, Ontario	Water Quality Criteria
Robert Ostry	Ministry of the Environment 1 St. Clair Ave.,West Toronto, Ontario	Water Quality of Grand River
Paricia Bonner	International Joint Commission Windsor, Ontario	Librarian
Dr. John M. Casselman	Ministry of Natural Resources Maple Research Station Maple, Ontario	Pike Family - growth and environmental requirements
Peter J. Colby	Ministry of Natural Resources Fish and Wildlife Research Branch Thunder Bay, Ontario	Walleye
Douglas Craig	Ministry of the Environment Centennial Plaza Stoney Creek, Ontario	Computer Search and Water Quality
Gordon Craig	Ministry of the Environment Resources Rd. Toronto, Ontario	Fish Toxicity Tests and Water Quality Criteria
Deborah Devlin	Ministry of the Environment Queen's Park Toronto, Ontario	Herbicides
John R. Foster	Ontario Hydro	Fish Behaviour and Industrial Impact Studies (Fisheries)

Appendix 1. (cont'd)

Name	Affiliation	Specialization
Dr. Richard Frank	University of Guelph Guelph, Ontario	Pesticides and Agricultural Practices
Jim Fraser	Ministry of Natural Resources Maple Research Station Maple, Ontario	Brook trout
Neil G. MacLean	Ministry of Natural Resources Nanticoke Fish Study Port Dover, Ontario	Fisheries - Impact Assessment
Peter Mason	Grand River Conservation Authority Cambridge, Ontario	Aquatic Biology, Grand River Watershed
Roberta McCelland	Freshwater Institute 501 University Crescent Winnipeg, Manitoba	Librarian
Dr. Al McCombie	Ministry of Natural Resources Maple Research Station Maple, Ontario	Rainbow trout
John Percy	Ministry of the Environment Simcoe, Ontario	Pesticides
Dr. John B. Sprague	University of Guelph Guelph, Ontario	Effects of Pollutants on the Aquatic Environment
Al Wainio	Ministry of Natural Resources Fisheries Branch Queen's Park Toronto, Ontario	Sports Fisheries

Appendix 2. Fish species mentioned in text (scientific and common names)

Common Name	Scientific Name
Brook trout	*Salvelinus fontinalis*
Rainbow trout	*Salmo gairdneri*
Brown trout	*Salmo trutta*
Cutthroat trout	*Salmo clarki*
Atlantic salmon	*Salmo salar*
Chinook salmon	*Oncorhynchus tshawytscha*
Gizzard shad	*Dorosoma cepedianum*
Northern pike	*Esox lucius*
Chain pickerel	*Esox niger*
Muskellunge	*Esox masquinongy*
Carp	*Cyprinus carpio*
Goldfish	*Carassius auratus*
Fathead minnow	*Pimephales promelas*
White sucker	*Catostomus commersoni*
Channel catfish	*Ictalurus punctatus*
White perch	*Morone americana*
Rock bass	*Ambloplites rupestris*
Smallmouth bass	*Micropterus dolomieui*
Largemouth bass	*Micropterus salmoides*
Pumpkinseed	*Lepomis gibbosus*
Bluegill	*Lepomis macrochirus*
Perch	*Perca flavescens*
Walleye	*Stizostedion vitreum*

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