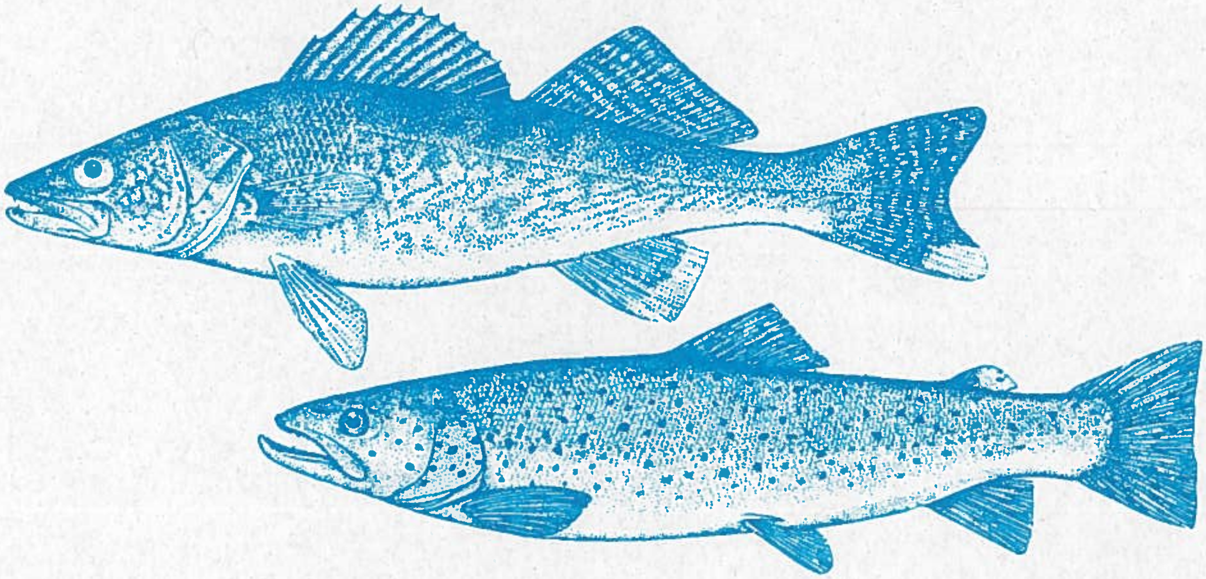
TEMPERATURE AND DISSOLVED OXYGEN CRITERIA FOR ALBERTA FISHES IN FLOWING WATERS



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RE: **TEMPERATURE AND DISSOLVED OXYGEN CRITERIA**

Dear Criteria Workshop Participant:

Environmental Management Associates is pleased to forward a copy of the document, **Temperature and Dissolved Oxygen Criteria for Alberta Fishes in Flowing Waters,** for your use. Although we were not able to address all concerns in this revision because of limited time and resources, we sincerely appreciate and acknowledge the input of all workshop participants. Our intent is to provide this to you now as a working document, with the understanding that it can be improved and expanded in future as needs arise and new information becomes available.

Thank you for your participation, your feedback, and your patience.

Sincerely,

ENVIRONMENTAL MANAGEMENT ASSOCIATES

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BAB:dt
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TEMPERATURE AND DISSOLVED OXYGEN CRITERIA FOR ALBERTA FISHES IN FLOWING WATERS

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PREFACE

There is a need to develop temperature and dissolved oxygen (DO) criteria for sport fish in Alberta that are tailored to the requirements of the numerous species and stocks, and their various life stages. Previous "single number" criteria were designed to protect the most sensitive life stage. But by doing so, such criteria may be overprotective of other life stages or less sensitive species, thereby restricting management options for water bodies. Conversely, single number criteria may be too broad in some instances to restrict water uses where necessary.

The objective of this document is to provide temperature and dissolved oxygen criteria for selected Alberta fishes that provide for the protection of critical life stages while still retaining the flexibility for reasonable water use and other fisheries management options. This document is not meant to provide rigid or legally binding criteria for Alberta waters. Rather, it is meant to serve as a guideline for fisheries biologists and managers evaluating the status of Alberta waters, who need to know how severely and how often normal temperature and DO levels may be exceeded maintaining healthy fish populations. The criteria are intended to be provincial; hence, some refinements of the criteria particularly regarding timing and duration of life stages to suit unusual populations or habitat conditions, may be necessary.

The document is presented in three parts. Part I presents the species-specific temperature and dissolved oxygen criteria, Part II discusses the background and rationale for establishment of the criteria, and Part III contains a statement on future research needs. Rather than being a final product, this document represents the first step towards establishing acceptable temperature and dissolved oxygen criteria for all sportfish species and their important stocks in the province. More information on individual species, their stocks, and the requirements of their various life stages is still needed, however. As new experimental and empirical data become available, they can be applied to revise and improve these criteria accordingly.

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PART I: SPECIES-SPECIFIC CRITERIA

1.0 INTRODUCTION

Derivation of temperature and dissolved oxygen (DO) criteria for Alberta fishes has been based on the approach developed by the U.S. Environmental Protection Agency and have been made specific to the seasonal migrations and life cycles of the individual species; an explanation of this approach is decribed in detail in Part II. The criteria are interpreted in terms of tolerable frequencies of exceedence, given the expected time necessary for populations of each species to recover from a disturbance. The following sections derive the criteria for individual species and species groups based on a review of temperature and DO requirements of their life stages. The focus of this report is on fishes in flowing waters. It is intended that this review be a working document to serve as a guideline for biologists and managers. Specific criteria and background information will be refined continually as new information becomes available and expanded to include additional riverine species and those from lacustrine habitats.

2.0 SPECIFIC CRITERIA FOR TEMPERATURE

2.1 RAINBOW TROUT

Rainbow trout (*Oncorhynchus mykiss*) spawn primarily from mid-April to late June (Scott and Crossman 1973). In Alberta eastslope waters, spawning can occur as late as July but is generally in late spring (Paetz and Nelson 1970; Brown 1971). In Bow River tributaries, for example, rainbow trout spawn from early May to early June (McDonald 1975). In general, spawning temperature is about 10 to 15°C (Scott and Crossman 1973) but may be lower in Alberta. McDonald (1975) found, for example, that peak spawning in Ware Creek occurred when water temperatures rose from 7.7 to 11.7°C. Native rainbow trout of the Athabasca River drainage may have requirements slightly different from those of introduced stocks elsewhere in the province and specific criteria may be required eventually to suit this unique stock. For example, rainbow trout in the Tri-Creeks system begin spawning in late May to early June when water temperature reaches about 6°C (Nip 1991).

The ultimate incipient lethal temperature (the lethal temperature that cannot be raised by acclimating fish to warmer water) for rainbow trout is about 26°C (Hokanson et al. 1977; Threader and Houston 1983; EPA 1986a; see Table 1). Applying the 2°C conversion factor to allow for zero mortality (see Part II) gives 24°C as the familiar acute temperature criterion for rainbow trout (Table 2). For acute exposures, only the maximum temperature and its duration matter; the rate of temperature change, as long as it takes place within one or a few days, makes no difference to the incipient lethal limit (Coutant 1973; Bidgood 1980). Long-term temperature changes are subsumed under chronic effects.

Acclimation also makes only a small difference. Upper incipient lethal temperatures for trout acclimated to different temperatures are presented in Table 3; generally there is only a small increase in lethal limits at higher acclimation temperatures, a resistance

TABLE 1

SOME EXAMPLES OF ACUTE THERMAL TOLERANCE LIMITS FOR RAINBOW TROUT

LIFE STAGE	TEMPERATURE (°C)	EFFECT	NOTES	SOURCE
Yearlings	27 28 29	400 min LT_{50} 100 min LT_{50} <60 min LT_{50}	acclimated to 20°C	Craigie 1963
Yearlings, <4.5 cm long	26 26.5	UILT (low 0_2) UILT (high 0_2)	acclimated to 18°C low 0_2 = 3.8 mg/L high 0_2 = 7.4 mg/L	Alabaster and Welcomme 1962
Young	25	UILT*	acclimated to 24°C	Cherry et al. 1977
Adults	26	UILT		EPA 1986a
Young Adults (5-12.5 cm long)	24-25	UILT	reared at 10°C	Bidgood 1980

* UILT - ultimate incipient lethal temperature.

TABLE 2

RAINBOW TROUT TEMPERATURE CRITERIA

LIFE STAGE	
Spawning	1 April - 15 June 7 consecutive days with: daily minimum ≥5°C daily maximum ≤10°C
Incubation	15 April - 15 August 320 TU subsequent to spawning with: daily minimum ≥7°C daily maximum ≤14°C
Adult-Acute[1,2]	daily maximum 24°C
Adult-Chronic	7-day mean <12°C or >19°C
Fry-Acute[1,2]	daily maximum 24°C
Fry-Chronic	7-day mean <12°C or >19°C

[1] Acute criteria should be reduced 1°C when the dissolved oxygen conditions in the river are less than the chronic criterion (7-day mean).

[2] Criteria should be reduced 2°C if the acclimation temperature (average river temperature) is less than or equal to 10°C.

TABLE 3

EFFECT OF ACCLIMATION TEMPERATURE ON ACUTE THERMAL TOLERANCES OF RAINBOW AND BROWN TROUT

SPECIES	LIFE STAGE	ACCLIMATION TEMPERATURE (°C)	INCIPIENT LETHAL TEMP. (°C)	DIFFERENCE (°C)	REFERENCE
Rainbow Trout	Young-of-the-Year	6	24.6	18.6	Stauffer et al. 1984
		12	25.9	13.9	
		18	26.7	8.7	
		24	26.0[1]	2.0	
Rainbow Trout	Fry (3 g)	4	22.8	18.8	Threader and Houston 1983
		8	24.1	16.1	
		12	24.6	12.6	
		16	25.4	9.4	
		20	15.9[1]	5.9	
Brown Trout	Juveniles	5	22.7[2]	17.7	Elliot 1981
		10	24.4	14.4	
		15	25.6	10.6	
		20	26.5	6.5	
		22	26.7	4.7	

[1] ultimate incipient lethal temperature.
[2] upper tolerances based on 1000-minute exposure.

typical of salmonid species in general (Stauffer et al. 1984). Rainbow trout acclimated to cyclically varying temperatures have thermal tolerance limits approximately 1°C higher than those acclimated at constant temperatures, at least at lower acclimation temperatures (<15°C) (Lee and Rinne 1980; Threader and Houston 1983), although Thomas et al. (1986) suggested that fish held in such regimes may experience greater physiological stress. Threader and Houston (1983), using their own data and extensive literature, found that the only pronounced effect of acclimation was that upper incipient lethal temperatures declined from 26 to 24°C at acclimation temperatures <10-12°C. This change has been incorporated into the criteria in Table 2. For application, the weekly average temperature is taken as the acclimatization temperature of the fish. Fry, juvenile and adult trout have about the same temperature tolerances (Bidgood 1980; see Table 1). Other life stages, however, are much more sensitive. Egg development and hatching are extremely temperature-sensitive, and proceed best at 5-10°C (Table 4). Serious embryo mortality begins at temperatures of 15°C or greater (EPA 1986a; Rombough 1988). Although 20°C is considered the safe limit to prevent disruption of spawning behaviour by thermal stress (Bell 1986), egg survival likely would be low at that temperature.

Chronic temperature criteria for rainbow trout are less precisely defined. The criteria given in Table 2 are based on knowledge of optima and thermal tolerance limits (see Part II). Optimal temperatures and normal ranges for rainbow trout are given in Bell (1986), Pederson (1987), and Stevenson (1987) for adults and spawners; Data for embryos are from the sources in Table 4. The EPA (1986a) independently derived very similar limits.

2.2 CUTTHROAT TROUT

Westslope cutthroat trout (*Oncorhynchus clarki*, var. *lewisi*), the stock found in Alberta waters (Liknes and Graham 1988), generally spawn from April to July, when water temperature is about 10°C (Scott and Crossman 1973). Bell (1973 *in* Hickman and

TABLE 4

ACUTE THERMAL TOLERANCES OF RAINBOW TROUT GAMETES AND EMBRYOS

LIFE STAGE	TEMPERATURE (°C)	EFFECT	NOTES	SOURCE
Eggs, sperm	<5	best survival of gametes	40 min exposure before fertilization	Billard and Gillet 1975
	5-15	best fertilization		
Embryos	5.3 - 10.5	optimal temperature	optimum rose as development proceeded	Alekseeva 1987
Eggs	10	best hatching success	tested 8-16°C	Kashiwagi et al. 1987
Embryos	15	15% mortality and impeded development		Rombough 1988
	≤12	4% mortality, normal development		

Raleigh 1982) reported that cutthroat trout spawned at temperatures ranging from 6 to 17°C, but this does not necessarily indicate an optimal range. In Alberta, Andrekson (1949 *in* Carlander 1969) reported that cutthroat trout in the Sheep River spawned from the beginning of June to the middle of July. In the Livingston River drainage, cutthroat trout may start moving into tributaries in early May and remain as late as early July, but most spawning occurs during the month of June (G. Clements, personal communication); in Station Creek, active spawning has been observed between June 2 and July 4, inclusive.

Scott and Crossman (1973) reported that hatching usually takes place 6-7 weeks after spawning, but no incubation temperature was indicated. Snyder and Tanner (1960 *in* Carlander 1969) found that eggs hatched in 30 days at 10°C, with an additional 2 days required for each 0.55°C below that temperature. This is equivalent to 300 temperature units (TU, see Part II), a thermal requirement similar to that of 300-310 used in Alberta hatcheries (W. Schenk, personal communication) and to that of 310 TU stated by Liknes and Graham (1988). An optimum thermal regime for incubation is not reported for cutthroat trout, but Calhoun (1966) indicated that rainbow trout embryos developed normally at ≤12°C but mortality became apparent <7°C. Thus, 7-12°C is considered as a suitable thermal regime for cutthroat trout egg incubation as well (Table 5).

Although Bell (1973 *in* Hickman and Raleigh 1982) considered the preferred temperature range for cutthroat trout to be 9 to 12°C, their greatest scope for activity (see Part II) was at 15°C (Dwyer and Kramer 1975). Based on those findings, Hickman and Raleigh (1982) selected 12 - 15°C as the optimal range for cutthroat trout. Hickman and Raleigh (1982) stated that adult cutthroat trout do not persist in waters where maximum temperatures exceed 22°C consistently. Behnke (1979 *in* Hickman and Raleigh 1982) reported that cutthroat trout of the Lahontan basin may be found in waters at 25°C, but the westslope cutthroat trout is a genetically distinct stock (Behnke 1988) and, thus, may have evolved with quite different thermal tolerances. Therefore, 22°C was established as the acute daily maximum for cutthroat trout, rather than 24°C as

TABLE 5

CUTTHROAT TROUT TEMPERATURE CRITERIA

LIFE STAGE	
Spawning	15 May - 15 July 7 consecutive days with: daily minimum ≥7°C daily maximum ≤10°C
Incubation	15 May - 15 August 310 TU subsequent to spawning with: daily minimum ≥7°C daily maximum ≤12°C
Adult-Acute[1,2]	daily maximum 22°C
Adult-Chronic	7-day mean <12°C or >19°C
Fry-Acute[1,2]	daily maximum 22°C
Fry-Chronic	7-day mean <12°C or >19°C

[1] Acute criteria should be reduced 1°C when the dissolved oxygen conditions in the river are less than the chronic criterion (7-day mean).

[2] Criteria should be reduced 2°C if the acclimation temperature (average river temperature) is less than or equal to 10°C.

determined for rainbow trout (Table 5). Upper incipient lethal temperature is not known for this species.

2.3 BROWN TROUT

Brown trout (*Salmo trutta*) spawn in the fall, primarily in November in Alberta (Paetz and Nelson 1970), but as late as January elsewhere in Canada, depending on conditions (Scott and Crossman 1973). Spawning temperatures for brown trout have been reported from 1 to 10°C (Elliot 1981) and from 1 to 8°C (Alabaster and Lloyd 1982), which are different from those of 8.8 - 12.8°C provided by Piper et al. (1982) for artificial culture.

Optimal temperatures for embryonic development of brown trout eggs were assumed by Raleigh et al. (1986) to be 2 to 13°C, based on earlier studies. But Davis (1953) suggested that the preferred range for brown trout egg incubation in hatcheries is 7 - 10°C. Given that brown trout eggs incubate over winter, however, a daily minima value of 7°C is unrealistic and the lower limit of 2°C is used (Table 6). About 410 to 440 TU (°C) are required at 10 to 4.4°C, respectively, for brown trout eggs to hatch after fertilization (Leitritz and Lewis 1976). These values are similar to the 381 degree-days at 11.2°C and 438 degree-days at 13.9°C calculated from temperature and time values cited in Raleigh et al. (1986)

Raleigh et al. (1986) concluded that a temperature range of 7 to 15°C is optimal for brown trout fry, whereas the overall tolerance range is 5 to 25°C. At temperatures above 25°C, mortality of brown trout fry may occur (Spaas 1960).

The upper lethal temperature for brown trout was given by Alabaster and Lloyd (1982) as 22.7 to 27.2°C, depending on acclimation temperature. Similarly, Elliot (1981) noted that both the acclimation temperature and time of exposure were important for determining upper lethal temperature. For example, upper lethal temperatures were from 25.6 up to 29.7°C for acclimation temperatures of 5 up to 22°C, respectively, for a

TABLE 6

BROWN TROUT TEMPERATURE CRITERIA

LIFE STAGE	
Spawning	15 September - 15 November 7 consecutive days with: daily minimum ≥5°C daily maximum ≤11°C
Incubation	15 September - 31 March 420 TU with <300 TU before 1 December: daily minimum ≥2°C daily maximum ≤10°C
Adult-Acute[1,2]	daily maximum 25°C
Adult-Chronic	7-day mean <12°C or >20°C
Fry-Acute[1,2]	daily maximum 23°C
Fry-Chronic	7-day mean <5°C or >15°C

[1] Acute criteria should be reduced 1°C when the dissolved oxygen conditions in the river are less than the chronic criterion (7-day mean).

[2] Criteria should be reduced 2°C if the acclimation temperature (average river temperature) is less than or equal to 10°C.

10-min exposure, but were 21.5 up to 24.7°C for these acclimation temperatures for a 7-day exposure. Although the upper lethal temperature for brown trout cited by Raleigh et al. (1986) was 27.2°C, the data of Elliot (1981) indicated that for brown trout acclimated to 20°C, more typical of Alberta streams in summer, the upper lethal temperature (1000 min test exposure) was 26.5°C (Table 3). The upper acute temperature limit was, therefore, set at 25°C to provide the zero mortality safety factor (Table 6).

The optimal temperature range required for good growth and survival of adult brown trout is 12 - 19°C (from various references *in* Raleigh et al. 1986), although Elliot (1981) determined the optimal overall range for this species was 4 - 19°C. Final preferenda for brown trout was 17.4°C, calculated by curvilinear regression by Cherry et al. (1977), and 17.6°C, determined by Ferguson (1958). Using the value of Cherry et al. (1977) as the optimum and that of Elliot (1981) as the upper lethal limit, the calculated upper chronic criterion (EPA 1986a) is 20°C. The temperature optima for juveniles was considered to be 7 to 19°C, with the optimum for growth being 12°C (Raleigh et al. 1986).

2.4 BULL TROUT

Like other chars, bull trout (*Salvelinus confluentus*) are fall spawners, and populations in Canada may spawn from September to November (Scott and Crossman 1973). Similarly in Montana, bull trout spawn from September to November (Brown 1971). Bull trout spawning has occurred as early as August in Oregon (Pratt 1989), but in the Flathead River system, Montana, most spawning took place during September and early October (Fraley and Shepard 1989).

Initiation of spawning is temperature-related and bull trout spawn when temperatures are <10°C. Fraley and Shepard (1989) reported that bull trout spawning began when temperatures dropped below 9-10°C, and in British Columbia, McPhail and Murray (1979) established 9°C as the threshold temperature for the initiation of spawning.

Based on Alaskan studies cited by Scott and Crossman (1973), the anadromous counterpart of this species, the Dolly Varden (*Salvelinus malma*), was found to spawn at 7.8°C.

In general, hatching is complete 100-145 days after fertilization (McPhail and Murray 1979; Allan 1980; Weaver and White 1985). Fraley and Shepard (1989) found that the time required to 50% of eggs hatched was 113 days at 1.2-5.4°C, and that the fry emerged from the incubation substrate 223 days after initial egg deposition. The best survival of bull trout eggs occurred at 2-4°C and egg mortality was evident at >8°C (McPhail and Murray 1979). About 350-440 TU are required for bull trout egg hatching (Weaver and White 1985; Gould 1987). An additional 65-90 days post-hatching are needed for yolk sac absorbtion (Gould 1987).

As bull trout is a relatively new species designation separate from the coastal Dolly Varden, there is very little thermal tolerance information available. Empirical observations and documented temperature requirements for spawning and egg incubation suggest that this species has a cooler thermal regime than other salmonids in Alberta. Pratt (1984) found that bull trout distribution in the Flathead River basin, Montana, was restricted to streams with maximum summer temperatures <15°C. Young-of-the-year bull trout were associated with cold springs or ground water (K. Pratt, personal communication).

Preferred and avoidance temperatures of related *Salvelinus* species are generally lower than for *Oncorhynchus* species. For example, the final preferendum for brook trout (*Salvelinus fontinalis*) is as much as 3 - 4°C lower than that for rainbow trout (Cherry et al. 1977) and upper avoidance temperatures are lower (Coutant 1977). Preferred and upper avoidance temperatures are also much lower for lake trout (*Salvelinus namaycush*) (Coutant 1977). Given their observed distribution and apparent range overlap with cutthroat trout in relatively cold waters (G. Clements, personal communication), acute and chronic criteria for cutthroat trout have been assigned to bull trout in the absence of suitable empirical data. The criteria in Table 7 are therefore interim, and will need to be revised as new information becomes available. As this genus generally has lower thermal limits than other trout genera, it would be important and timely to develop such criteria as soon as possible because of the special concern status of bull trout in Alberta (Johnson 1987).

2.5 MOUNTAIN WHITEFISH

Mountain whitefish (*Prosopium williamsoni*) are fall spawners, although some stocks may spawn as late as early February in British Columbia (McPhail and Lindsey 1970). In general, mountain whitefish in Alberta spawn in October through early November (Paetz and Nelson 1970), with southern populations spawning mainly in October (Alberta Environment 1986). Similarly, mountain whitefish spawn in late October and early November in Montana (Brown 1971) and northern Idaho (Sigler and Sigler 1987). Further south in Utah, spawning occurs in November and early December (Sigler 1951). In southern Alberta, Thompson (1974) found that mountain whitefish in the Sheep River exhibited spawning movements as early as September 29 and as late as October 18, but most of the spawning occurred between October 4 and 10. In the Crowsnest River, spawning mountain whitefish were observed between October 7 and 15 (R.L. & L. 1986), and mountain whitefish spawning in the Oldman River took place in late September through mid-October (EMA 1986).

Initiation of mountain whitefish spawning is probably related to declining water temperature, although actual water temperature data from field studies are limited. Brown (1952) observed that spawning movement was initiated at 5.5°C in Montana and Thompson (1974) found that spawning movements began when water temperature was ≤6°C. Brown (1971) reported that Montana mountain whitefish populations spawn when water temperatures are between 1.7 and 7.2°C. In northern Idaho, spawning temperatures ranged from 4.4 to 7.2°C (Sigler and Sigler 1987). The U.S. Fish and

TABLE 7

BULL TROUT TEMPERATURE CRITERIA

LIFE STAGE	
Spawning	15 August - 15 November 7 consecutive days with: daily minimum ≥1°C daily maximum ≤9°C
Incubation	15 September - 31 March 350 - 450 TU with <300 TU before 1 December: daily minimum ≥1°C daily maximum ≤7°C
Adult-Acute[1,2]	daily maximum 22°C[3]
Adult-Chronic	7-day mean <12°C[3] or >15°C
Fry-Acute[1,2]	daily maximum 22°C[3]
Fry-Chronic	7-day mean <12°C[3] or >15°C

[1] Acute criteria should be reduced 1°C when the dissolved oxygen conditions in the river are less than the chronic criterion (7-day mean).

[2] Criteria should be reduced 2°C if the acclimation temperature (average river temperature) is less than or equal to 10°C.

[3] Where published information is lacking for bull trout, criteria for cutthroat trout have been used based on observations of their reported coexistence in similar habitat of eastslope streams.

Wildlife Service habitat suitability model for mountain whitefish suggests spawning occurs between 0 and 7.2°C, with the peak (i.e. HSI = 1) occurring at 3°C.

Incubation of eggs takes place over the winter with hatching occurring in spring. The optimum temperature for embryonic development is 4°C (Siefert et al. 1984) and normal development and hatching success may by impaired at temperatures >6°C (Rajagopal 1979). Rajagopol (1979) found that egg mortality at ≥9°C was far greater than at 6°C. Thus, 6°C was established as the upper incubation temperature criterion (Table 8). Mountain whitefish in Utah take about 5 months of incubation to hatch at a temperature >1.7°C (Sigler and Sigler 1987). Thompson (1974) found that hatchery incubation of mountain whitefish eggs at 7.5°C resulted in most eggs hatching in 50 to 61 days. Hatching time was 59 to 63 days when water temperature was 7.2°C (Stalnaker and Gresswell 1974) but was 36 days at 11°C (Brown 1952). Extrapolating these findings leads to a thermal requirement of 396 to 439 TU for mountain whitefish egg incubation. This extrapolation is based on empirical observations of time to hatch, and water temperatures may not have been consistent throughout the incubation period. Moreover, TU requirement varies with temperature and, without testing experimentally, it is difficult to specify the precise thermal requirement for embryonic development at the optimum temperature of 4°C. As a guideline, 430 TU is recommended to encompass incubation temperature regimes in Alberta streams (Table 8).

Few precise data are extant on thermal tolerance limits of mountain whitefish. The criteria given here (Table 8) are necessarily provisional and are largely based on observed temperature preferences and extrapolation from other salmonid species. A temperature of 12°C is considered optimum for fry (after yolk-sac absorption) and juvenile mountain whitefish (Rajagopol 1979; Ihnat and Bulkley 1984). However, juvenile mountain whitefish are found in water up to 20.6°C (Ihnat and Bulkley 1984). Assuming fish would avoid chronically harmful temperatures, but allowing a 2°C factor for uncertainty, 18°C has been used as the chronic thermal limit for juveniles; adults frequent the same temperature range as juveniles, so their chronic limit is also 18°C

TABLE 8

MOUNTAIN WHITEFISH TEMPERATURE CRITERIA

LIFE STAGE	
Spawning	15 September - 15 November 7 consecutive days with: daily minimum ≥1°C daily maximum ≤6°C
Incubation	15 September - 1 April 430 TU subsequent to spawning with: daily minimum ≥1°C daily maximum ≤6°C
Adult-Acute[1,2]	daily maximum 22°C
Adult-Chronic	7-day mean <8°C or >18°C
Fry-Acute[1,2]	daily maximum 24°C
Fry-Chronic	7-day mean <8°C or >18°C

[1] Acute criteria should be reduced 1°C when the dissolved oxygen conditions in the river are less than the chronic criterion (7-day mean).

[2] Criteria should be reduced 2°C if the acclimation temperature (average river temperature) is less than or equal to 10°C.

(Table 8). On the other hand, Davies and Thompson (1976) found that mountain whitefish fry in the Sheep River frequented shallow (25 cm), exposed, currentless backwaters that must have become quite warm on sunny days in May and June. The acute thermal limit for whitefish fry was therefore elevated to 24°C (Table 8). The acute criterion of 18°C for spawning fish is based on the observation of Ihnat and Bulkley (1984) that pre-spawning fish caught in October always preferred temperatures <18°C, even after acclimation, indicating a reduced thermal tolerance at that season.

Unfortunately, acute thermal tolerances for adult mountain whitefish have not been measured. Provisional limits are prescribed here based on the observation that temperature optima for whitefish are usually 1-2°C cooler than for rainbow trout. Hence, 22°C, and 20°C when weekly average water temperature is <10°C, have been used as the acute thermal limits for adult mountain whitefish (Table 8).

2.6 LAKE WHITEFISH

There is a dearth of information on temperature and oxygen requirements of riverine lake whitefish (*Coregonus clupeaformis*) and the criteria developed have been extracted from studies of lacustrine populations of this species. Lake whitefish are late fall spawners, spawning in Alberta from October to December (Paetz and Nelson 1970). Other lake whitefish populations in Lake Erie, Great Slave Lake, Montana, and the Yukon also have been observed to spawn at this time (Carlander 1969; Scott and Crossman 1973), but Bidgood (1974) documented lake whitefish in Pigeon Lake, Alberta, spawning from late September through to January. An appropriate spawning period for southern Alberta waters would be October 1 to December 30. Although spawning has been apparently observed at temperatures as high as 10°C (Hart 1930), other investigators document lake whitefish spawning at temperatures between 0.5 and 5.5°C (see Carlander 1969). Similarly, Morrow (1980) indicated that lake whitefish in Alaska spawn at <6°C and Bidgood (1974) observed spawning occurring between 1.2 and 7°C. Moreover, Lawler (1965) reported that spawning did not begin in Heming Lake, Manitoba, until temperatures dropped to <7.8°C. Thus, recommended a spawning temperature range for lake whitefish is 0.5 - 6°C (Table 9).

The optimum temperature for lake whitefish egg incubation appears to be about 0.5°C (Price 1940). Egg mortality was lowest at that temperature and increased with increasing temperature above 4°C to almost 100% at 10°C. Similarly, egg fertility decreased when temperature was increased from 5 to 8°C (Wickliff 1933). However, in a more recent laboratory study, survival was optimal at 4 to 6°C, but was minimal at 10°C (Griffiths 1979). Similarly, Brooke (1975) found that optimum temperatures for lake whitefish eggs were from 3.2 to 8.1°C and survival was greatly reduced at temperatures outside of that range. Davis and Behmer (1980) concluded that the harmful effects of elevated temperatures (e.g. 10°C) occur only during the early period of incubation.

Incubation time appears to be a more important factor than thermal units in determining the number of days from fertilization to hatching, possibly because of the low incubation temperatures involved. Price (1940) found that the time to hatch was 140 days at 0.5°C (70 TU) and Van Oosten (1956) observed a hatching time of 120-140 days at 0.5-1.7°C (60 and 238 TU). Brooke (1975) found that 112 to 182 incubation days were required for temperatures of 0.5 to 4°C and M. Drouin (personal communication) observed that 150 to 190 days were needed at 1.3 to 2°C. Under fluctuating temperatures, 200-300 TU were required for incubation at mean temperatures between 1 and 2°C, but >400 TU were determined for temperatures >5°C (calculated from data of M. Drouin, personal communication). Similarly, TU for incubation was >400 for temperatures >4°C, but were 91 and 306 for 0.5 and 2°C, respectively (from data *in* Brooke 1975). Bidgood (1974) reported, however, that it took 191-192 days at 2°C (382 TU) and 144-156 days at 4°C (600 TU) for eggs held under controlled conditions to hatch after fertilization. An appropriate incubation period guideline would be total days that can accommodate the increasing thermal units required as incubation temperature increases in the spring. Allowing an appropriate number of days between lake whitefish spawning (e.g.

TABLE 9

LAKE WHITEFISH TEMPERATURE CRITERIA

LIFE STAGE	
Spawning	1 October - 31 December daily minimum ≥0.5°C daily maximum ≤6°C
Incubation	1 October - 30 May 170 days subsequent to spawning with: daily minimum ≥0.5°C daily maximum ≤5°C
Adult-Acute[1,2]	daily maximum 23°C
Adult-Chronic	7-day mean <12°C or >20°C
Fry-Acute[1,2]	daily maximum 23°C
Fry-Chronic	7-day mean <12°C or >18°C

[1] Acute criteria should be reduced 1°C when the dissolved oxygen conditions in the river are less than the chronic criterion (7-day mean).

[2] Criteria should be reduced 2°C if the acclimation temperature (average river temperature) is less than or equal to 10°C.

November) and hatching (e.g. mid-April) would provide about 160-170 days for incubation over the winter at low temperatures (Table 9).

There is very little information available on acute or chronic lethal temperatures for adult lake whitefish. Christie and Regier (1988) reported that the optimum range for lake whitefish appeared to be 10-14°C. This is similar to the final preferendum of 11.9°C for this species cited by Coutant (1977), although that value was based on a field survey conducted in 1945. McCormick et al. (1971) calculated that the upper chronic limit for cisco (*Coregonus artedi*) a related species, to be 18.6°C, based on the average between the optimum temperature and that which produced zero net growth. Similarly, Edsall and Colby (1970) proposed an upper limiting temperature for cisco of 19°C, which was one-third of the range between the optimum and upper incipient lethal temperatures. These values are similar to the upper avoidance value of 20°C cited by Coutant (1977) and the threshold value of 20°C of the upper critical range for *Coregonus lavaretus*, a similar European species, cited by Elliot (1981). In the absence of experimental data, an upper chronic limit of 20°C to reflect upper limits for related species is suggested for lake whitefish (Table 9). There are no data for upper acute temperatures for lake whitefish, but Elliot (1981) indicated graphically an upper critical limit for Coregonidae of 25°C (based on *C. lavaretus*). If the 2°C safety factor is applied to this value, then a suggested acute temperature criterion is 23°C (Table 9).

There are no published values on lower limits for *Coregonus* species except a value of about 1°C presented graphically by Elliot (1981). Therefore, the suggested criteria in Table 9 are presented as interim only, and are subject to revision as additional data become available.

Similarly, there is little information for lake whitefish fry, although indications are that they prefer warmer temperatures than adults as other coregonids do. Reckahn (1970) observed that lake whitefish fry in Lake Huron preferred temperatures of 17°C. Coutant (1977) cited other final preferendum values of 15.5, 13.5, and 12-16°C for fry of decreasing sizes; upper and lower avoidance temperatures were 17-19 and 12-14.5°C, respectively. Recent culture studies indicated that lake whitefish fry appeared to be stressed and did not readily accept feed at temperatures of 16-18°C (M. Drouin, personal communication). It appears that, although preferred temperature of fry may be higher than adults, the preferred temperature may change rapidly with early growth and their tolerance range is narrow. For lack of better information, 23°C (same as adult) as an upper acute limit and 18 and 12°C as upper and lower 7-day chronic limits are suggested as criteria (Table 9).

2.7 WALLEYE AND SAUGER

Walleye (*Stizostedion vitreum*) are classed as coolwater fish and have higher thermal tolerances and requirements than salmonid fishes. According to Scott and Crossman (1973), walleye spawn in the spring when temperatures are in the range of 6 to 11°C, but mostly between 7 and 9°C. However, in Alberta, walleye are known to spawn when temperatures are about 4-5°C (Paetz and Nelson 1970). Colby et al. (1979) suggested that a cooling period for spawning success may be necessary; although there is considerable variation among stocks in spawning temperatures, most upper temperatures appear to be <10°C. Water temperatures <10°C appear to be necessary for proper gonadal maturation over the winter (Hokanson 1977) and optimum temperatures for egg fertilization are 6 to 9°C (Koenst and Smith 1976).

Koenst and Smith (1976) found that optimum temperatures for incubation were 9 to 15°C. Steady warming rates (e.g. >0.2°C/day) during the period of egg incubation appear to be required for good survival (Busch et al. 1975). Data cited in Colby et al. (1979) indicated that egg mortality can be expected to be high when temperatures are >20°C, but there is considerable stock difference. Hokanson (1977) found that lower and upper tolerance limits of embryonic walleye were <6°C and 19.2°C. Similarly, Smith and Koenst (1975) indicated that upper lethal temperatures for walleye embryos are near 19°C. Thus, the incubation criteria were established at 6 and 18°C (Table 10).

TABLE 10

WALLEYE TEMPERATURE CRITERIA

LIFE STAGE	
Spawning	15 April - 1 June 5 consecutive days with: daily minimum ≥5°C daily maximum ≤12°C
Incubation	15 April - 1 July 170 TU subsequent to spawning with: daily minimum ≥6°C daily maximum ≤18°C
Adult-Acute[1,2]	daily maximum 29°C
Adult-Chronic	7-day mean <15°C or >24°C
Fry-Acute[1,2]	daily maximum 29°C
Fry-Chronic	7-day mean <15°C or >24°C

[1] Acute criteria should be reduced 1°C when the dissolved oxygen conditions in the river are less than the chronic criterion (7-day mean).

[2] Criteria should be reduced 2°C if the acclimation temperature (average river temperature) is less than or equal to 10°C.

At temperatures of 8 up to 15°C, eggs hatch in 21 down to 14 days (Ney 1978), or 168 and 210 TU, respectively. Koenst and Smith (1976) found that it took 3 weeks at 10°C and 1 week at 20°C for walleye eggs to hatch, or 210 and 140 TU, respectively. Similarly, incubation at constant hatchery temperatures has resulted in hatching times of 4 days at 23.9°C (96 TU) to 33 days at 4.5°C (149 TU) (data presented *in* Colby et al. 1979). However, in rapidly fluctuating temperature regimes, the TU requirement will be considerably higher (Piper et al. 1982).

Upper lethal temperatures indicated for adult walleye are 29 to 32°C, and 31.6°C for juveniles (Hokanson 1977), although Wrenn and Forsythe (1978) reported higher lethal temperatures for adults. Optimum growth temperatures for walleye are 20 to 24°C (various authors *in* McMahon et al. 1984) and adults apparently avoid temperatures >24°C (Fitz and Holbrook 1978). Adult growth ceases at temperatures <12°C (Kelso 1972). Final preferenda for walleye have been found to range from 20.6 to 23.2 (data cited *in* Coutant 1977 and Hokanson 1977).

Juvenile walleye appear to have higher temperature requirements than adults. Piper et al. (1982) indicated that the optimum range for fry survival was 15 - 21°C. Upper lethal temperatures for fry are 31 to 33°C (Smith and Koenst 1975; Wrenn and Forsythe 1978), and lower and upper limits for growth are 12 and 29°C (Kelso 1972; Hokanson 1977). Optimum growth of juveniles occurs between 19 and 25°C, notably at 22°C (various authors *in* Colby et al. 1979). Nickum (1986) reported that 20°C is generally satisfactory for fingerling rearing in intensive culture. Until a more extensive review is conducted, temperature criteria for walleye in Table 10 may be considered applicable for sauger (*Stizostedion canadense*) as well.

3.0 SPECIFIC CRITERTIA FOR DISSOLVED OXYGEN

3.1 TROUT SPECIES

Suggested DO criteria for trout species, whitefishes, and non-salmonid fishes are presented in Table 11. The majority of the research on DO requirements of salmonids, upon which the EPA (1986b) criteria are based, has been done with rainbow trout (e.g., see references in Davis 1975). These criteria are designed to apply to salmonids generally. Comparative available data suggest that all trout have quite similar DO requirements, but that tolerance of brown trout to low DO is slightly greater. First, in river systems, trout species usually partition themselves with brown trout in the lower reaches and rainbow trout or brook trout in upstream reaches, where water tends to be colder and perhaps more nearly O_2-saturated. Second, brown trout, even more so than rainbow trout, have been successfully introduced into many waterbodies in a variety of climates on six continents (Scott and Crossman 1973). Such adaptability suggests a tolerance of a wider range of conditions than is typical of salmonids. Thirdly, a number of growth tests for various salmonids under different DO regimes (EPA 1986b) indicated that the reduction in growth rate of brown trout at any given DO level is slightly less than that for rainbow trout, but about equivalent to that for other salmonids.

Extensive DO criteria are lacking for salmonids other than rainbow trout; the substantial amount of experimental work on thermal and oxygen limits that has been conducted with rainbow trout has not been repeated with most of the species of concern in Alberta. However, much of the preceding general discussion will apply to those other species as well. In their review, Hickman and Raleigh (1982) stated that optimal DO levels for cutthroat trout appear to be >7 mg/L at temperatures ≤15°C and higher for warmer temperatures, and that this species avoided concentrations <5 mg/L. Optimum DO levels for adult brown trout appear to be in the range of 9-12 mg/L, depending on temperature (Raleigh et al. (1986). Like most salmonids, incipient lethal effects become

TABLE 11

DISSOLVED OXYGEN CRITERIA FOR SALMONID AND NON-SALMONID FISHES

	SALMONIDS		
LIFE STAGE	TROUTS	WHITEFISHES	NON-SALMONIDS
Early Life-Acute Daily Minimum	8.0[1]	5.0	5.0
Early Life-Chronic 7-Day Mean	9.5[1]	6.5	6.0
Fry-Acute Daily Minimum	5.0	5.0	5.0
Fry-Chronic 7-Day Mean Minimum	5.5	5.5	5.0
7-Day Mean	6.5	6.5	6.0
Adult-Acute Daily Minimum	4.0	4.0	3.0
Adult-Chronic 7-Day Mean Minimum	5.0	5.0	5.0
7-Day Mean	6.0	6.5	5.0

[1] Values are for the water column to achieve an intergravel DO concentration 3 mg/L lower.

apparent when DO levels are ≤3 mg/L (Dourdoroff and Shumway 1970). In the absence of special criteria for adults and eggs, general salmonid criteria are adopted. For fry, Raleigh et al. (1986) recommended minimal DO concentrations of >3 mg/L when temperature is ≤15°C and >5 mg/L when temperature is >15°C.

3.2 WHITEFISHES

As DO criteria are designed to apply to salmonids generally, they are assumed to apply to whitefishes as well. The only possible exception is the criterion for whitefish fry. The EPA (1986b) and Davis (1975) apply the early-life-stage criteria to embryos and all juveniles up to one month after hatching. This is reasonable for trout, but Davies and Thompson (1976) found newly emerged mountain whitefish fry inhabiting shallow, still backwaters that presumably had significantly lower DO concentrations than the main channel. Thus, the DO criteria for early life stages may be overprotective of these fish. Other life stages appear to be more similar to trout. Augmentation of criteria to account for interstitial DO concentrations is not required for mountain whitefish, who are broadcast spawners. That conclusion is supported by the work of Siefert et al. (1974) who found that survival of mountain whitefish eggs and larvae incubated at 4°C was the same at DO concentrations of 12 or 6.5 mg/L, and growth rates were similar. Incubation time was prolonged by two weeks at the lower DO tension. At a DO level of 4.6 mg/L, however, survival and growth rate at 100 days after hatching were significantly reduced. At DO levels of 3.3 mg/L or less, hatching success, growth, and survival declined drastically (Siefert et al. 1974).

There are few data available to generate specific dissolved oxygen requirements for lake whitefish. Doudoroff and Shumway (1970) reported lethal levels of generally <3 mg/L for a number of European and Asian whitefishes, which were similar to those reported for other salmonids. Coregonid fishes were not included in the extensive review by Davis (1975) of oxygen requirements for Canadian species. The criteria for mountain whitefish are therefore recommended for lake whitefish also. In the absence of extensive experimental data on O_2 requirements of coregonid fishes, the general criteria for salmonids has been adopted (Table 11).

3.3 WALLEYE AND SAUGER

Dissolved oxygen criteria for walleye cannot be verified because the acute lethal concentration has not been determined for adults of this species. The limited data that are available are compiled in Table 12. Colby et al. (1979), as part of a comprehensive synopsis of the biology of walleye, indicated that 2 mg/L may be tolerated by adults in the laboratory, but cite no experimental work. Scherer (1971) found behavioural disruption an eventual loss of equilibrium at DO levels of $\leq$1.5 mg/L. Perturbation of normal behavioural patterns at low DO levels could seriously impair feeding performance of walleye as these fish feed at night or early morning when DO levels would be at their daily minimum.

An acute DO criterion of 3.0 mg/L, as a 1-day minimum, would appear to be adequate to protect walleye populations. Except during very earliest life, walleye are opportunistic piscivores, feeding predominantly on species of smaller fish that are available (Scott and Crossman 1973; Lyons 1987). Those benthic invertebrates that are taken are generally tolerant, large-river forms such as chironomids, amphipods, mollusca and burrowing mayflies (Craig and Smiley 1986; Ritchie and Colby 1988; Fox 1989) that do not require high DO levels. The only exception is newly hatched larvae, which feed on zooplankton and other invertebrates for the first 1-2 months, until they are large enough to consume fish (Walburg 1972; Raisaren and Applegate 1983). Hence, to maintain a healthy walleye population, a healthy and diverse population of forage fishes must be maintained; criteria provided by EPA (1986b) are designed to apply to warmwater (including coolwater) species generally and, therefore, should achieve this objective.

More data are available on DO requirements of young walleye (Table 12). From experimental and aquacultural experience, it appears that >5 mg/L of DO is optimal for

TABLE 12

SUMMARY OF LOW DISSOLVED OXYGEN EFFECTS ON WALLEYE

LIFE STAGE	DO LEVEL (mg/L)	EFFECT	SOURCE
adult	2	tolerance limit in laboratory	Colby et al. 1979
populations	>3	"most abundant in natural waters"	Colby et al. 1979
adult (1+)	1.5 - 2 <1.5	loss of light-avoiding behaviour loss of equilibrium (probably fatal)	Scherer 1971
adult	1.1 - 1.6	mortality	Hoff and Chittenden 1969
embryo	5 - 6 <5 3	optimum for incubation, 12 - 13°C reduced hatching success severely reduced hatching success; 10 - 13% shorter larvae than at 7 mg/L	Oseid and Smith 1971
embryo/larva	5.0 3.4 2.5 5.7 - 7.3 <3 5.3	95% survival after 20 days 40% survival no survivors at 24°C, considered optimum for hatcheries 1 hour exposure, >25% mortality no mortality after 1 day	Siefert and Spoor 1974

embryos and young larvae of walleye, and that concentrations much below 3.5 mg/L are likely to lead to reduced survival. The criteria have been set at 5.0 mg/L as a 1-day minimum and 6.0 mg/L as a 7-day mean (Table 11). It is important to ensure these criteria are sufficiently protective, because survival of earliest life stages is seen as a key control of walleye populations (Noble 1972; Scott and Crossman 1973).

As both species are physiologically and behaviourally similar, the DO criteria for walleye in Table 11 may be considered applicable as interim criteria for sauger.

PART II: BACKGROUND AND RATIONALE

1.0 INTRODUCTION

Traditionally, temperature and dissolved oxygen (DO) criteria for protection of aquatic life were applied as single numbers (e.g. 5 mg/L DO and 24°C for salmonids), defining fixed limits to be met at all times (EPA 1976). This was a reasonable first approximation, especially given the newness of the field and the level of knowledge of aquatic ecology at the time. In the past decade there have been large advances in our understanding of the dynamics of aquatic ecosystems and their component species. As well, increasing human demands on waterbodies have required that protection criteria be defined more rigorously. Dissolved oxygen requirements and temperature tolerances of aquatic species vary according to season, age, health, and stage of the life cycle (EPA 1990). Therefore, any fixed, single-number criterion risks providing insufficient protection at one time, while being overly protective at another. Most fish, for example, require temperatures much lower than their physiological limit to stimulate spawning behaviour (Lindsay et al. 1959; Biette et al. 1981). Some life stages, in particular embryos and newly hatched alevins, have higher DO requirements than adults (EPA 1990).

For migratory species, such as most salmonids, the seasonal presence of the fish in any given reach is a further argument against fixed water quality criteria. Certain temperature regimes act as cues to stimulate migration (Lindsay et al. 1959) and therefore should not be disturbed. On the other hand, it is inefficient and unnecessary to comply rigidly with a fixed water quality criterion when the species (or life-stage) it is designed to protect is not present.

A more sensitive approach is to tailor the temperature and DO criteria to the time-dependent needs of the biota. A fixed criterion would be replaced by a set of criteria for each season, month, or week, as required, that are adequate to fully protect the most sensitive species or life stage known to be present at that particular time. When spawning is underway or young, intolerant life stages are present, for instance, the criteria would be set stringently to ensure their protection. At other seasons when only adult fish are present or sensitive species have migrated elsewhere, the criteria would be relaxed, thus allowing further human uses of river water.

A second assumption of the older, single-number criteria was that these were absolute limits, never to be exceeded if the ecosystem was to be protected. This assumption was based on the understanding at the time that lotic ecosystems were essentially stable and free from disturbance, with their internal structures determined largely by biotic interactions, such as predation and competition (EPA 1986b). A coherent body of research has now emerged showing that aquatic ecosystems are more dynamic than previously thought, and stochastic disturbances, such as floods and droughts, are important structuring influences on them (Resh et al. 1988). Consequently, aquatic species are naturally adapted to a certain level of disturbance, and anthropogenic disturbances such as exceedences of DO or temperature criteria, need not be catastrophic as long as they are within the range of frequency and intensity to which a particular species is adapted (EPA 1986b). Hence, the seriousness of occasional criteria exceedences needs to be examined in light of the natural frequency of such exceedences, independent of human intervention. Given that some exceedences are inevitable under natural conditions, the present approach promotes maintaining the natural regime of extreme events (disturbances) rather than treating every violation of a fixed criterion as an unacceptable occurrence.

2.0 TEMPERATURE

The EPA (1986a) defines two upper temperature limits for any given aquatic species. The first limit is a maximum temperature to avoid mortality from short-term temperature shock and is termed the acute limit. The second, termed the chronic limit, defines maximum temperatures for longer (weeks to months) exposures and is designed to prevent mortality from cumulative stress or physiological impairment, and to prevent disruption of seasonal activities such as spawning and migration. Each of these limits must be specific not only to a particular species, but also to the particular life stages (eggs, alevins, fry, adults) that are likely to be present at any given time.

2.1 ACUTE CRITERIA

The temperature that is fatal to an adult fish depends on the duration of exposure. An extreme temperature will be quickly fatal, while a more moderate temperature may cause death only after hours or days of exposure (Coutant 1973). As a result, a logarithmic plot of time to death of 50% of a sample population (LT_{50}) against temperature will be approximately linear, with a steep negative slope defined by:

$$\log \text{Time} = a + b\,(T_c)$$

where:
Time = time to death (hours)
T_c = exposure temperature (critical temperature)
a, b = constants

An acute lethal temperature for any given exposure time is derived by simply rearranging the equation to solve for T_c. But to define a safe limit for the species, the LT_{50} line must be translated to an LT_0 line, i.e. the upper limit of temperatures that will result in zero mortalities rather than 50%. Numerous studies have shown that for any given combination of temperature and exposure duration that produces 50% mortality in a population, a temperature 2°C less produces zero mortality (Coutant 1973). Based on this reasoning, the EPA (1986a) defined the time-dependent acute temperature criterion (T_a) as:

$$T_a = \frac{[\log(\text{Time}) - a] - 2°C}{b}$$

This criterion requires that the lethal time-temperature relationship be known to define **a** and **b**, and is chiefly intended to guard against temperature shocks from heated effluents or cooling-water plumes. Such a criterion should not be necessary for natural waters, if indeed the data were available to define it, because water temperatures at any location are not likely subject to these types of rapid fluctuations. Exceptions to this generalization may occur when natural waters receive inputs of artificially heated water such as from thermal electric generating stations, industrial complexes, or sewage treatment plants.

An acute temperature criterion for rivers and streams unaffected by heated effluent plumes may take advantage of the fact that temperatures will vary predictably through a range of at least several degrees every day. As a consequence of this sinusoidal pattern, fish are unlikely to be exposed continuously to critical (i.e. stressful) temperatures for more than 5-6 hours, and at most 10-12 hours, on any given day, even during periods of hot weather. But for the same reason, if the peak temperature of the day exceeds the lethal limit, the fish will also be subjected to several hours of sublethal temperatures both before and after exposure to the lethal temperature that could be severe enough to cause stress or physiological harm even if they are not immediately fatal. That is, the critical temperatures do not occur as sudden "spikes" in natural waters, but as gradual increases followed by gradual declines. These two points lead to the conclusion that fish can be exposed to critical temperatures in flowing waters for 10-12 hours at a time and, therefore, the acute criterion for any given species should be a single figure that protects against exposures of that duration. Ten hours occurs between 500 and 1000 minutes, two standard times for measuring fish survival in laboratory tests. Because of the exponential relation between survival time and declining temperature, 10 hours is also a time close to the asymptote of the time-temperature curve, often called the incipient upper lethal temperature (Coutant 1973; Cherry et al. 1977). This latter number is the one most often reported in the scientific literature. The lethal temperatures at 500 minutes and 1000 minutes and the upper incipient lethal temperature differ by <1°C, which is less than the uncertainty in lethal temperature determinations.

Because thermal tolerance limits vary with acclimation temperature (e.g., Table 3) acute temperature limits should be reduced 2°C for seasons of weekly average water temperature <10°C, to account for acclimatization.

Finally, the synergistic effect of other stressors must be considered. Temperature tolerance limits are typically derived using still water and well-fed, unstressed fish exposed in aquaria where only temperature varies. In natural systems, fish are subjected to stress from any number of stressors simultaneously, of which low oxygen tension, fatigue, and hunger are the most prominent (Schneider et al. 1973). Alabaster and Welcomme (1962) exposed young trout to extreme temperatures in water containing either 7.4 mg/L or 3.8 mg/L dissolved oxygen. The lethal temperature for any particular survival time was reduced about 0.5-0.8°C in the presence of low oxygen tension. Extrapolating this result to other life stages, the acute thermal criteria should be reduced 1°C for low DO conditions (Tables 2, 5-10). For application,"low" DO is defined as a concentration less than the chronic criterion (7-day mean) for that week and life stage given in the subsequent sections. Effects of other stressors cannot be explicitly included.

In summary, the acute temperature criterion for flowing waters in Alberta should be based on the assumption that potentially lethal temperatures could be experienced for periods of 10-12 hours. An exceedence of the criterion would be deemed to occur whenever the daily maximum temperature exceeds the criterion for one hour or more because, given the sinusoidal pattern of water temperature, the daily maximum temperatures for several hours before and several hours after critical temperature exceedence will also approach or exceed the criterion.

2.2 CHRONIC CRITERIA

Temperature limits for long-term exposures are more difficult to quantify because they do not lend themselves to simple experimental determination as acute limits do. The central intent of chronic limits is to avoid causing possibly debilitating thermal stress and the metabolic changes associated with it, and to maintain the normal life cycle of the fish concerned. Temperature criteria are designed as population safety limits, beyond which the long-term viability of the population will be compromised. This effect may be outwardly apparent as reduced numbers of fish, reduced growth rates, poorer condition, and lower overall production and recruitment.

Temperature is the most important factor controlling the rate of metabolism in fish. For fish generally, a 10°C increase in temperature results in a greater than two-fold increase in metabolic rate ($Q_{10} = 2.3$). There are many factors that affect how fish respond to changes in temperature; important among these are life stage, acclimation history, and digestive state (Elliot 1981), as well as duration of exposure.

In a classic paper, Fry (1947) outlined the concept of scope for activity, defined as the difference between the maximum energy output possible (active metabolism) and the minimum required to survive (standard metabolism) at a given temperature. In other words, scope for activity represents the energy available to the fish for all other functions (routine activity, disease resistance, predator avoidance, growth and reproduction, etc.) after basic metabolic needs are satisfied. There is a temperature range, different for each species, within which the scope for activity is greatest, or wherein the fish is most efficient metabolically (Figure 1). Within this range, fish have their maximum performance capacity and it often includes or overlaps with their preferred temperature zone, i.e., the one that they select behaviourally. A preferred or selected temperature is

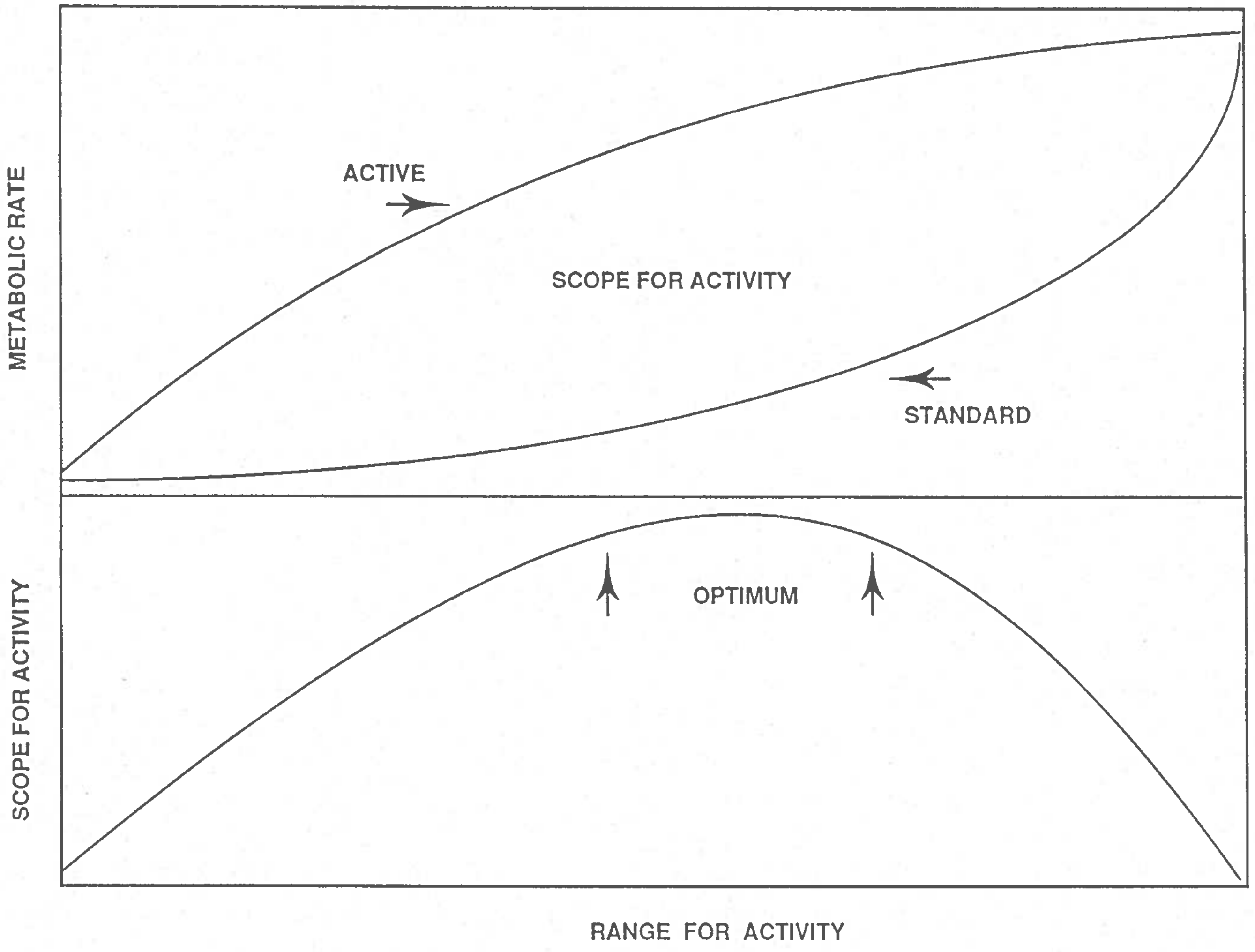

Figure 1. Diagrammatic representation of the change in scope for activity over the range of an environmental condition (e.g. temperature) for activity. The optimum is the range where scope for activity is greatest.

the water temperature where fish may be most frequently found (Elliot 1981). Fish are usually found in maximum abundance in their zone of preference; regularly, but not abundantly, in their zone of tolerance; and occasionally outside of those zones when conditions are unusual (Andrewartha and Birch 1954 *in* Royce 1984), for example, for short periods during migrations or feeding. However, if fish are out of their preferred (optimum) range indefinitely, they may experience stress effects, such as: reduced growth, cessation of feeding, abnormal swimming activity, increased ventilatory activity, reduced reproductive success, reduced body condition from lower fat content, and reduced food conversion efficiency (Elliot 1981).

Central to the establishment of chronic temperature limits is the idea of temperature optima. As outlined above, every physiological function of a fish has a certain temperature range within which it will function normally; the optimum temperature, which may be seldom experienced by a fish in a natural environment, will be somewhere (not necessarily the middle) in the acceptable range. Moreover, other environmental factors may affect the optimum or preferred temperature. For example, Schurmann et al. (1991) found that final preferred temperatures of rainbow trout declined with decreasing levels of oxygen tension of the water. Temperatures outside the normal physiological range but below the incipient lethal temperature are not directly fatal, but may lead to dysfunction of the process concerned, be it growth, hatching, or spawning.

Normal physiological ranges may be narrow compared with the acute tolerance range of the species. Therefore, one suggested approach to establishing chronic temperature criteria was to use the average of the physiological optimum temperature and that of zero net growth (NAS 1972). More recently, the EPA (1986a) defined chronic temperature criteria as the physiological optimum temperature for the function of concern (usually growth) plus one-third of the difference between that temperature and the upper incipient lethal limit. That equation defines a limit that lies reasonably close to where the edge of the normal range may be expected to lie (Coutant 1973). Since optima are usually known or may be inferred for most species, this method would prove adequate where more exact data are not available. For some species, rates of physiological processes have been measured at a variety of temperatures, and the chronic temperature criteria may be estimated directly as those temperatures that lie within, but at the limit of, the normal range of those processes.

Weekly average temperatures are normally used for comparison with chronic criteria (EPA 1986a). A week is the lower limit for effects considered chronic, is the smallest block of time likely to embrace a complete stage of the life cycle (such as spawning), and corresponds roughly to the time needed for fish to fully acclimatize to a new temperature (Coutant 1973; Cherry et al. 1977). Ideally, chronic temperature criteria should be applied against weekly moving average temperatures.

2.3 OPTIMUM TEMPERATURES

Although this document is intended to provide temperature and DO guidelines as a step toward evaluating effects of exceedence, fisheries managers are rightfully concerned with optimum temperatures in their attempts to provide fish populations the maximum degree of protection possible. Optimum temperature ranges for the fishes described in this document are presented in Table 13. The values were obtained from multiple sources, but particularly the U.S. Fish and Wildlife Service Habitat Suitability Information report series, and are open to revision as new data become available.

2.4 INCUBATION PERIODS

Within the appropriate temperature range, fish eggs require a certain number of days to incubate that is generally a function of temperature; the higher the temperature, the less time is needed from fertilization to hatching. Traditionally, the product of the temperature and time required for hatching was referred to as "degree-days" and was a useful method for estimating time for eggs to hatch in a hatchery. However, the relationship between temperature and time for embryonic development is not linear.

TABLE 13

OPTIMUM TEMPERATURE RANGES (°C FROM LITERATURE) FOR FISHES IN NATURAL WATERS

SPECIES	EGG INCUBATION	FRY	JUVENILE	ADULT	SPAWNING MIGRATION
Rainbow Trout	7-12	13-19	15-20	12-18	2-16
Cutthroat Trout	7-12	unavailable	≈15	12-15	unavailable
Brown Trout	2-10	7-15	7-19	12-19	<9 (to initiate)
Bull Trout	2-4	unavailable	unavailable	<15	<9 (to initiate)
Mountain Whitefish	≈4	≈12	≈12	unavailable	≈3 (<6 to initiate)
Lake Whitefish	4-6	12-16	unavailable	10-14	unavailable
Walleye	9-15	≈22	20-24	20-24	6-11

The term "temperature units" (TU) is now used to describe the thermal requirements (temperature X time) for fish to hatch and for most species, the TU requirement itselfvaries with temperature (Piper et al. 1982; Figure 2). As precise thermal requirements for egg incubation at different temperatures are not well established for most species, TU and degree-days are often the same for practical purposes, including this report. Moreover, it is unlikely in nature that incubating eggs would be exposed to constant temperatures as they are in a hatchery, as temperatures fluctuate both seasonally and diurnally. Thus, it is not realistic to use TU to calculate the precise incubation time unless thermal regimes are known. However, TU, or degree-days, are useful for providing an approximation of that period. In the absence of experimental data, empirical observations have been used to estimate incubation times required in natural populations and these often form the basis of habitat protection guidelines. It is therefore recommended that actual dates be used, in addition to temperature units, to establish critical periods for incubation criteria. Dates provided here are those cited for timing constraints on construction in and around watercourses in Alberta (Alberta Energy and Natural Resources 1986).

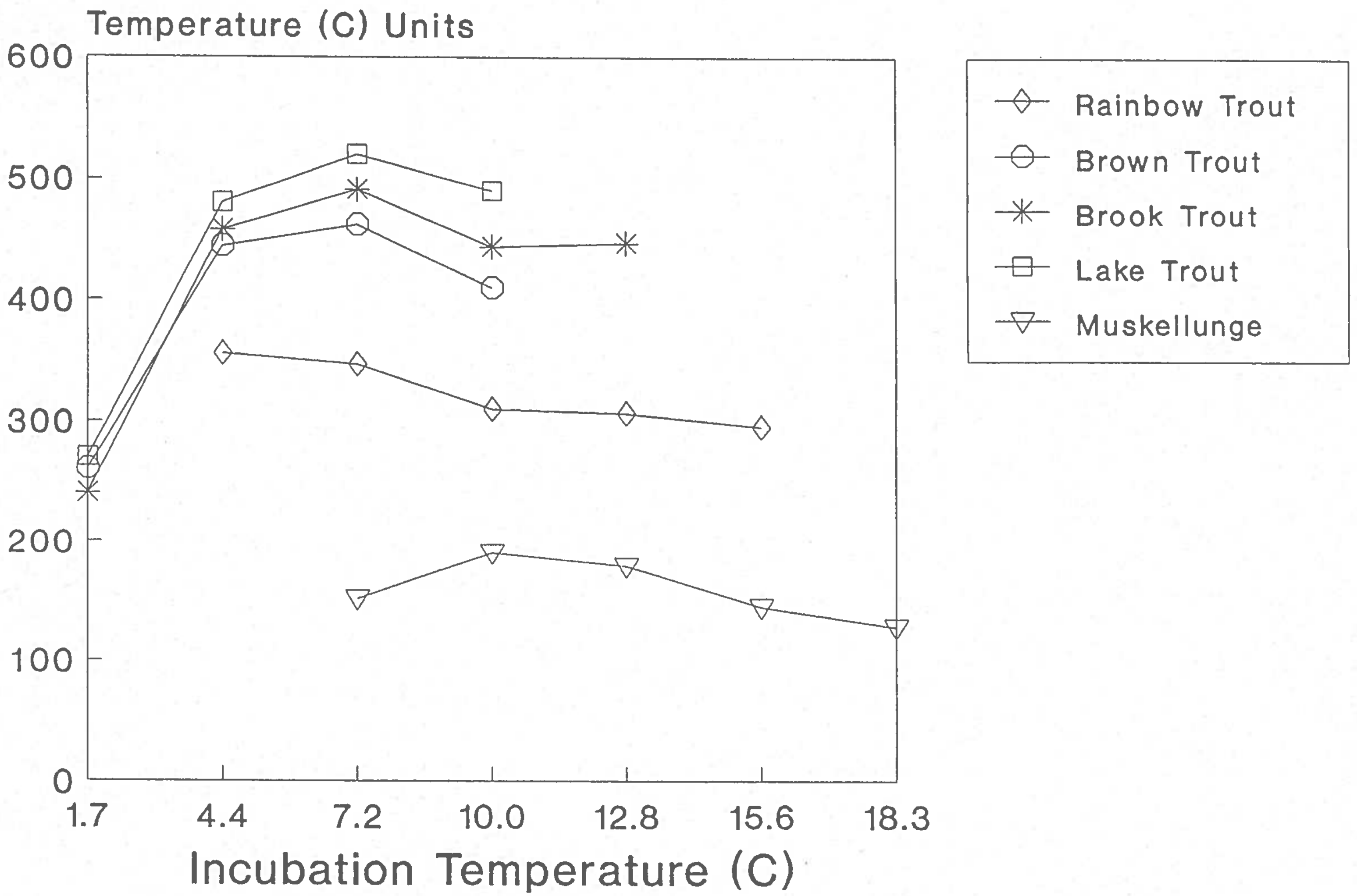

Figure 2. Relationship between incubation temperature and temperature units (TU) required for hatching (modified from Piper et al. 1982).

3.0 DISSOLVED OXYGEN

A sizeable and broadly consistent body of literature has now emerged on the DO requirements of freshwater aquatic life. While there remain many inconsistencies in measurement, results, and interactive effects of DO levels with other environmental factors, there are sufficient reliable data on a broad range of species to establish reasonable water quality criteria. Traditionally, separate DO criteria have been established for "coldwater" and "warmwater" biota. Coldwater fish species are almost exclusively members of the family Salmonidae (plus a few other species of similar sensitivity, such as smallmouth bass [*Micropterus dolomieu*]) that appear to have relatively high DO requirements. All other species are classed as warmwater species, although "non-salmonid" is a more useful term, as this group includes both warmwater fishes and "coolwater" species, such as walleye and northern pike (*Esox lucius*). Non-salmonid fishes generally have DO requirements at least 1 mg/L lower than those of salmonids, but because of the size of the group, individual species may depart from the normal.

In this document, DO criteria are expressed as concentrations. Gas exchange across the fish gill depends on the O_2 tension gradient between the internal environment (e.g., blood) and the external environment (e.g., water). Oxygen tension, or partial pressure, depends not only on the concentration of O_2 in the water, but also other physical and chemical properties of the environment, particularly water temperature, atmosperic pressure, and salinity; the latter is of no significance in Alberta. As the temperature increases, the ability of water to hold DO decreases. As atmospheric pressure increases, the ability of water to hold DO also increases. Thus, the solubility of O_2 in water decreases with increasing altitude. Therefore, for a fixed DO concentration, its saturation level (expressed as percent of complete saturation) will be lower at low temperatures than at high temperatures and will increase slightly with altitude. The saturation values in Table 14 derived for a DO concentration of 5 mg/L are similar to those of Davis (1975b) for salmonids to provide a medium level of protection but with some degree of risk to the population if minimum levels persist. EPA (1986b) concluded that DO

TABLE 14

PERCENT SATURATION OF OXYGEN IN WATER AT REPRESENTATIVE TEMPERATURES AND ALTITUDES IN ALBERTA WHEN THE MEASURED OXYGEN CONCENTRATION IS 5 mg/L (DERIVED FROM FORMULA IN APHA 1985).

TEMPERATURE (°C)	ALTITUDE (m)		
	500	750	1000
5	50	51	53
10	56	58	60
15	63	65	67
20	70	72	74
25	77	79	82

criteria expressed as percent saturation are complex and may result in unnecessarily stringent criteria during cold months and potentially unprotective criteria during periods of high ambient temperatures or at high elevations.

Both acute and chronic DO criteria are necessary to fully protect fish populations. Acute criteria protect the fish against short-term, usually fatal, low DO levels. Chronic criteria protect against stress or decreased production from long-term exposures to sub-optimal DO levels. Establishment of acutely lethal DO levels is relatively straightforward and can be accomplished in the laboratory. In theory, an LC_{50} value (the DO concentration quickly lethal to 50% of the test organisms) can be established in the same manner as for other toxicants. In practice this approach is seldom done and lethal DO levels must be inferred from mortality rates of fish exposed to gradually diminishing oxygen concentrations (Doudoroff and Shumway 1970).

Derivation of chronic criteria is more difficult. Doudoroff and Shumway (1970) pointed out that, based on many studies on many species, there is evidently no concentration level by which the DO level of natural waters can be reduced without risking some adverse effects on the growth or reproduction of fishes inhabiting those waters. In other words, the DO level, like temperature and food supply, acts as a limiting factor on fish population production. Hence, any reduction of DO levels may proportionately reduce production. Yet DO levels well below full saturation, as often occur naturally, may still permit the long-term persistence of a healthy fish population. The task then, in setting chronic DO criteria, is to choose the average DO level that is consistent with production sufficient to sustain the fish population.

Consideration of these factors led to the set of DO criteria in Table 11 proposed for trout species, whitefishes, and non-salmonids, specifically walleye. The DO criteria proposed are modified from those developed by the EPA (1986b), the most complete and recent criteria available. EPA (1986b) incorporates or considers a number of earlier reviews and criteria documents (e.g. Doudoroff and Shumway 1970; Davis 1975; EPA

1976; IJC 1976; Alabaster and Lloyd 1980) as well as more recent literature. The EPA criteria include four periods of averaging DO concentrations, from one day to one month. The 30-day mean limit is intended to protect against stress and reduced [illegible] production and growth from prolonged exposure to sub-optimal DO levels. The same end is accomplished by a 7-day mean limit for eggs and larvae, which persist for such short periods that a 30-day average is not sufficiently protective. Here, the 30-day mean limit for adult fish has been expressed as a 7-day mean, both for simplicity and to be consistent with the temperature criteria, whose application is dependent on DO levels. The remaining criteria are a 7-day mean minimum (that is, the mean of the nightly minimum DO values each week) applied to adult fish, and a 1-day minimum applied to all life stages. The 1-day minima are referred to here as acute criteria and the 7-day values as chronic criteria.

The 1-day minimum criteria are designed to prevent acute mortality from low DO concentrations. However, as with temperature, there is a tendency for episodes of low night-time DO to occur serially; that is, a night of low DO levels is likely to be followed by several others, at least in summertime. Repeated exposures to dissolved oxygen tensions at or near the acute lethal threshold may still be a serious stressor, which can cause reduced growth, higher metabolic demands, and lowered resistance to other stressors, such as temperature, disease and pollution (EPA 1986b). The effects of such stressors may be cumulative (Barton and Iwama 1991) and chronic DO criteria are designed to protect aquatic populations against that possibility. The 7-day mean limits assure that DO levels are generally high enough to allow normal growth, metabolism and behaviour free from oxygen stress. Because DO concentrations oscillate daily, however, it is possible for mean DO levels to remain above criteria levels, and yet subject fish to critically low oxygen tensions at night. Guarding against this possibility requires a second chronic criterion, the 7-day mean minimum, which ensures that night-time DO minima near the acute lethal limit are not repeated in close succession. No such criterion is necessary for early life stages (embryos, alevins) because of their short duration, and because the difference between the 7-day mean and the 1-day minimum is small.

For purposes of calculation, 7-day means are to be computed as moving averages, not as fixed week-by-week means. Also, DO concentrations in excess of atmospheric saturation should be set to saturation before means are computed (EPA 1986a). There is no evidence that fish can profit from oxygen above saturation concentrations except in intensive artificial culture situations, and inclusion of such data can bias estimates of mean DO level, especially since systems prone to supersaturation are also prone to wide diurnal cycles.

The life cycle has been divided into three parts: (1) "early" stages include embryos and young larvae, (2) fry, and (3) adults. For trout, the early life stage ends when the alevins complete yolk-sac absorption, leave the protection of the redd, and begin feeding. For walleye, the early life stage includes the period when the newly hatched larvae leave the spawning grounds and disperse throughout the lake or river (Scott and Crossman 1973); this time is relatively short as the yolk sac is absorbed relatively quickly (Nickum 1986). In non-salmonid fish generally, the newly hatched larvae are considerably more sensitive to low DO levels than older fish (Doudoroff and Shumway 1970), and walleye larvae in particular, being initially too small to fight currents (Walburg 1972), cannot actively avoid episodes of low dissolved oxygen.

The structure of these criteria allows for the fact that both long-term and short-term exposures to low dissolved oxygen tensions are detrimental, and that DO levels, especially in rivers unperturbed by large organic waste loads, oscillate through a predictable daily cycle. The 1-day minimum criteria are designed to prevent acute mortality from low DO concentrations. Such periods of low oxygen occur at night (with minima just before dawn) and never last more than 10-12 hours before photosynthesis begins to increase DO concentrations in the water. However, repeated exposure to DO tensions at or near the acute lethal threshold still represents a serious stressor to the fish, which can lead to reduced growth, higher metabolic demands and lowered resistance to other stressors such as disease and pollution (EPA 1986b). Chronic DO criteria are designed to protect aquatic populations against that possibility. The 7-day mean limits assure that DO levels are generally high enough to allow normal growth, metabolism and behaviour, free from stress caused by low O_2. Because DO concentrations oscillate daily, however, it is possible for mean DO levels to remain above criteria levels, and yet subject fish to critically low O_2 tensions at night. To guard against this possibility requires a second chronic criterion, the 7-day mean minimum, which ensures that night-time minima near the acute lethal limit are not repeated in close succession. No such criterion is necessary for early life stages because of their short duration.

Experiments with rainbow trout exposed to acutely lethal hypoxia showed that heart arrythmia began after about one hour of exposure (Namba et al. 1987). Although the fish survived another one or two hours once arrythmia began, eventual death of the fish was inevitable, even when DO levels were raised quickly to 8 mg/L. Brown trout exposed to acutely lethal DO levels survived an average of <50 minutes at 1.0 mg/L, and 1.5 hours at 1.5 mg/L (Drewett and Abel 1983). Even if fish survive a low DO period, an episode of nearly lethal acute hypoxia imposes a severe stress that may seriously weaken the fish. On the basis of these experiments, a violation of a DO criterion should be taken to be any DO concentration below the criterion that persists for more than one hour, if continuous measurements are available, or any spot measurement or mean of spot measurements that is less than the criterion.

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The highest acutely lethal DO level reported for adult salmonids is near 3.0 mg/L (Davis 1975). However, DO criteria for salmonids are not intended solely for the direct protection of the fish themselves, but also to protect the physical and biological environment, and especially food species, that are necessary to sustain healthy salmonid populations (EPA, 1986). Thus, the criterion is set at 4.0 mg/L to protect invertebrate food species, many of which are more sensitive to low DO levels than are salmonids (EPA, 1986). For example, Gaufin (1973) and Nebeker (1972) together provide 96-hour LC_{50} values of dissolved oxygen concentrations for 26 species of aquatic insects, including plecoptera, ephemeroptera, trichoptera and diptera. Test temperatures were 6.4°C (Gaufin 1973) and 10.5°C (Nebeker 1972). The LC_{50} values varied from <0.6 mg/L for the midge, *Tanytarsus dissimilis*, to >5 mg/L for the fast-water mayfly, *Ephemerella doddsi*. Significantly, the LC_{50} for half of the species tested was 3-4 mg/L, indicating that at least 4 mg/L of DO is needed for populations to survive (EPA 1986b). All the species tested were collected from Montana and Minnesota, and thus should represent the kinds of invertebrates to be found in southern Alberta. A minimum DO of 4 mg/L would not necessarily protect all species of benthic invertebrates; many species, especially coolwater mayflies, have LC_{50} values well above that limit (Gaufin 1973; Jacob et al. 1984). Dissolved oxygen levels above 4 mg/L, however, are sufficient to maintain a healthy invertebrate community, although the species composition may change.

Acutely lethal DO minima are relatively easily defined, but somewhat higher DO levels may still be detrimental to fish health and production in the long term. Critical DO levels for growth, the best general index of health, are determined by finding the concentration at which physiological functions become oxygen dependent. For example, in trout at 15°C, the DO concentration controls food consumption below 6 mg/L, and growth and food conversion efficiency below 7 mg/L. Above those concentrations, the functions mentioned are independent of DO level (Pederson 1987). The critical oxygen concentration is that below which growth impairment may be expected, becoming increasingly severe as the mean DO level declines.

Therefore, long-term depression of DO concentrations below their natural level in a waterbody will be manifested more as a reduction of fish growth and production than as mortality. The depression of production is greatest when temperatures are high and food is abundant, and hence both metabolic demand and growth potential are greatest (EPA 1986b). There are parallel increases, as DO concentration declines, in susceptibility to stress, toxicants and disease. For example, Morrison and Piper (1986) found that below a DO concentration of 5.7 mg/L, growth rate, food conversion efficiency, and survivorship (140 days) of young brown trout all declined in direct proportion with DO levels.

Because of this continuum of effects of DO level, chronic criteria cannot be predicated upon a level of "no effect" as is often done for toxic substances. Rather, the approach has been to define families of criteria or equations that correspond to a given level of risk or protection of the fish population (Doudoroff and Shumway 1970; Davis 1975). The classes or levels of protection are usually defined qualitatively, because the exact degree of effect will vary according to the fish species, climate, food supply and many other uncontrolled factors. The EPA (1986b) has drawn on this earlier work and more recent data to define four levels of protection, corresponding with severe, moderate, slight or no production impairment. The no-impairment class requires very high DO levels (≥6 mg/L for non-salmonids and ≥8 mg/L for salmonids) and is probably only realized in pristine waterbodies. The EPA criteria are set 0.5 mg/L above the slight-impairment level, and thus represent the threshold at which production impairment begins.

The EPA (1986b) criteria have been applied here with one modification. Chronic criteria for adult fish, in the EPA schema, are intended to be met by a 30-day average DO concentration. For ease of application, all chronic criteria here are expressed as 7-day means. Shortening the averaging period decreases the potential duration of periods during which the ambient DO level can be below the criterion while still meeting it on average (EPA 1990). Thus, reducing the averaging period for chronic criteria is equivalent to raising the criterion. Consequently, the 30-day mean criteria from the EPA (1986b) of 6.5 and 5.5 mg/L have been reduced to 6.0 and 5.0 mg/L for adult salmonids and non-salmonids, respectively, for application to Alberta waters.

For trout eggs and alevins, which live within the stream-bottom gravel, the criteria are augmented by an additional 3 mg/L (Table 11) to compensate for the usual difference in DO level between interstitial water and the water column (EPA 1986b). The DO concentration gradient between the water column and interstitial water is dependent on water depth and velocity as well as substrate type. For example, fine sand substrates with organic deposits are likely to have lower interstitial oxygen levels than coarse gravel respect to temperature. Recent research has shown that for rainbow trout, DO requirements of the embryo increase through development to a peak just before hatching (Rombough 1988). Greatest critical DO levels were: 7.5 mg/L at 6°C, 8.9 mg/L at 9°C, and 9.6 mg/L at 12°C. Hence, the EPA criteria of 9.5 mg/L (7-day mean) and 8.0 mg/L (1-day minimum), which represent a compromise encompassing all early life stages, may not be completely protective of embryos, especially at higher temperatures, and when the concentration difference between substrate and water column is large. However, since the peak requirements at 12°C require water that is very nearly saturated (>89%), optimum conditions probably rarely occur in nature. The criteria in Table 11 are considered sufficient to ensure normal reproductive success and maintain a healthy population, though any unnecessary reduction in DO levels during egg development should be avoided.

* egg development in 15 April – 15 Aug.
major ↓ in flows = ↓ temp
= ↓ DO -
-what is viability to RainbowTrout.

4.0 FREQUENCY OF EXCEEDENCE

As outlined in the Introduction, derivation of the frequency with which temperature and DO criteria may be violated without incurring irreparable harm to fish populations, must consider the natural exceedence frequency and severity of such events. Criteria exceedences of limited magnitude and duration are not necessarily fatal, and if they fall within the frequency and severity to which the species is adapted, they may only be an additional stress to the population. Unless the stress is overly severe or long-lasting, fish are usually able to cope with such disturbances and, in fact, are naturally equipped to do so (Schreck 1981). Indeed, salmonid populations exposed naturally to midsummer temperatures periodically exceeding stress thresholds may be as productive as those in more sheltered environments (Bisson et al. 1988). Even occasional severe disturbances may be tolerated by the population if they are rare enough to allow complete recovery of the population in the interval.

For discussion, an exceedence will be taken as any temperature or dissolved oxygen level that violates a criterion. As shown, these are not usually directly fatal. Extreme events severe enough to cause substantial mortality will be termed disturbances, in keeping with the usual ecological definition of the word (Resh et al. 1988; EPA 1990). Acceptable frequencies of recurrence for exceedences and disturbances will be quite different. Disturbances during the summer months would cause a general depression of the population, without bias toward any particular age group, while disturbances in the spawning season are more likely to cause a year-class failure. In either situation, the tolerable disturbance frequency is that which ensures survival of enough adults to rebuild the population before the next disturbance is encountered. Any increase in frequency of minor exceedences beyond the natural rate must not increase the vulnerability of the population by reducing production, reproductive success, or resistance to disease, starvation or other stressors. The frequency of minor exceedences will also partly determine the recovery time needed after a disturbance.

The rate of recovery of a river ecosystem depends upon the severity of the disturbance, its duration, and the life-cycles of the species affected. The EPA (1990) cited studies showing that most river systems recovered from disturbances (defined as extreme events severe enough to cause death or displacement of organisms) within two years. Exceptions were unusually severe disturbances, or multiple disturbances in close succession, especially in larger rivers, or recovery of long-lived species of fish. Recovery times of up to 25 years may be required for a long-lived fish population to fully return to its previous density and structure. For example, Curtis (1990) reported that recovery of an isolated population of lake trout decimated by sea lamprey (*Petromyzon marinus*) took 20 years once control of the parasite was achieved; recovery required 10 years to reach a critical threshold and 10 more years of rapid population regrowth.

The rate of recovery also depends on whether reproduction or recolonization is the dominant mechanism. If there are refugia where organisms are protected from the disturbance or source areas within the watershed that support an unaffected population, then recovery through recolonization may be quite rapid. Recolonization of a small stream disturbed by a severe chlorine spill took less than one year for algae, invertebrates and non-territorial fishes but recovery of northern pike, a resident, territorial species that suffered a year-class failure, was expected to take 2-3 years (Heckman 1983).

Clearly, the life history of the species that criteria are designed to protect is also important to the acceptable frequency of exceedences. For example, rainbow trout and mountain whitefish both reach sexual maturity at 3-4 years of age, but mountain whitefish are much longer lived (>10 years compared with 6-7 years for rainbow trout [Scott and Crossman 1973]). Recovery of rainbow trout populations after a disturbance would, thus, be considerably faster than recovery of mountain whitefish.

Extreme events causing death of a significant part of the population require a fixed recovery time free of further disturbance for the population to recover. Based on the life cycle requirements of mountain whitefish, for example, it is recommended that disturbances should occur no more often than once every five years, regardless of the rate of minor exceedences. For species with shorter life cycles, a disturbance every three years or less may be tolerated.

Derivation of an acceptable frequency for minor exceedences is a challenging problem. The central question is this: Given that fish populations are adapted to a certain level of natural stress, how much additional stress can they accommodate before the long-term health and well-being of the population is compromised? Any environmental condition beyond the natural range to which a species is adapted poses a threat to the viability of the population. Therefore, the ultimate management goal should always be to reinstate the natural frequency of exceedences, with no additions from human influence. In the short term, however, the answer appears to depend on the temperature and DO regimes in the water where each fish population lives. Populations living in stable environments in the centre of their range may be able to tolerate a modest increase in the frequency of high temperature or low DO events without significant impairment of production. Conversely, populations living in marginal habitat, at the fringe of their geographical range, or that are already exposed to frequent minor disturbances would be very susceptible to further stress. In addition, the greater the frequency of exceedence is in any given year, the greater the probability is of an extreme event capable of causing acute mortality. Thus, for stressed populations it is important to reduce increases in the rate of minor exceedences to a minimum, and long-term management should be directed toward reducing the exceedence frequency to more closely approach the natural state.

PART III: FUTURE RESEARCH NEEDS

At a recent workshop held with fisheries staff of the the Alberta Fish and Wildlife Division (2-4 July 1991; Calgary, Alberta), a number of items were identified by participants that would be desirable to make temperature and DO guidelines more effective in Alberta. Many of these items require additional research and are listed as follows for consideration:

- Natural frequencies of exceedence for specified waters as a reference point by which to evaluate deviations from historical patterns.

- The causal relationship between a change in frequency of exceedence and a change in the fish population.

- The frequency of exceedence that can be tolerated by a given fish population before its health and well-being is compromised.

- Separate criteria for identified stocks of particular concern and for specific waters to incorporate differences in requirements.

- Criteria for the different stages of all other Alberta sport fishes not included in this document.

- The cumulative effect of criteria violation and interactive effects of other variables on fish populations and aquatic ecosystems.

- Additional information on temperature and DO requirements of individual species in order to refine the criteria.

- Additional knowledge of the life history stages and critical habitats of the target species.

- Quantification of present fish populations to compare with habitat conditions.

- Better information on interstitial DO levels and the gradient between water column levels.

GLOSSARY

active metabolism: rate of metabolism (measured as oxygen consumption) during maximum sustained activity.

acute: referring to an event or a response that has a sudden onset or which lasts only a short time (an *acute exposure*, an *acute response*). In toxicology, acute events are usually taken as those that last <96 hours (4 days). The acute response (to exposure to a toxicant or high temperature or low DO tensions) of interest is usually death, but coughing, or avoidance behaviour, or metabolic changes, can all be acute responses.

alevin: post-hatch fish with yolk sac still attached; sac fry.

arrythmia: irregular rhythm of heart beat.

chronic: Referring to an event or a response that is lingering or persists for a long time (a *chronic exposure*, a *chronic response*). Chronic exposures are usually taken as occurring over a significant part of the life cycle of the organism, usually weeks or months. A chronic response is often subtle and persistent, such as elevated blood enzyme levels or slowed growth, but death can also result from a chronic stress.

criterion: here, a temperature or dissolved oxygen concentration specified to protect the species of interest from death or physiological harm from high temperatures or low dissolved oxygen concentrations. *Acute criteria* protect the animals against brief exposures; *chronic criteria* protect against exposures of weeks or months. The criterion is the highest (or lowest) temperature (or DO tension) that with reasonable confidence can be said to cause no harm to the animals concerned.

critical: a general term here referring to any temperature or dissolved oxygen tension that (a) exceeds an acute lethal limit, or (b) approaches an acute or chronic physiological limit closely enough that the animals experience special metabolic demands to deal with it. The critical level of dissolved oxygen, for example, is the level below which the function of interest (usually growth or respiration efficiency) depends on the DO level.

digestive state: refers to the status of food still contained in the organism's digestive tract. A post-digestive state, for example, would be one where all food material in the gut has been digested and waste products eliminated.

disturbance: an extreme event severe enough to cause substantial mortality.

embryo: egg up to the time of hatching.

exceedence: any temperature or dissolved oxygen level that violates a criterion.

fatal: resulting in death; lethal.

fry: early post-stage of fish after yolk sac has been absorbed; swim-up fry.

incipient lethal limit: the maximum (minimum) temperature (DO concentration) tolerated indefinitely by 50% of the animals tested.

juvenile: generally considered as immature fish with one season of growth up to the age of first maturity.

lethal: capable of causing death; fatal. A lethal response (i.e. death) may result from an acute or chronic exposure to high temperatures or low DO concentrations.

limit: used here in the ordinary sense of a boundary or edge. The *lethal limit* for temperature is the highest temperature that an organism can withstand without dying. If the exposure is brief, then the temperature is the *acute lethal limit*. The lethal limit is sometimes termed the *tolerance threshold*.

performance capacity: in the context of energy availability, the potential to carry out activities beyond the minimum required for survival. For example, the energetic capacity to capture prey, escape predators, resist disease, etc.

Q_{10}: the factor by which metabolic rate increases for a temperature increase of 10°C. A generally accepted Q_{10} value for teleosts is 2.3.

standard metabolism: minimum rate of metabolism (measured as oxygen consumption) of an intact organism at rest in a postabsorptive (post-digestive) state and thermally acclimated.

stochastic: pertaining to chance; random; unpredictable.

stress: a change in biological condition or state, beyond the normal range of resting conditions, caused by an environmental stimulus that challenges homeostasis and, thus, represents a threat to the fish's well-being.

stress response: a biological response to stress in order to regain a normal resting or homeostatic condition.

stressor: any environmental condition sufficiently outside the preferred range of an organism that evokes a biological response in order to cope with the stimulus and maintain homeostasis. Typical stressors, or stress factors, are chemical (e.g. pH, pollutants, low DO), physical (e.g. handling), or thermal in nature

ultimate incipient lethal limit: the incipient lethal temperature limit that is realized when fish are acclimated to the warmest temperature possible; the highest incipient lethal limit obtainable.

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