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Effects of Total Dissolved Solids on Aquatic Organisms: A Review of Literature and Recommendation for Salmonid Species

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Abstract: Total dissolves solids (TDS) are naturally present in water or are the result of mining or some industrial treatment of water. TDS contain minerals and organic molecules that provide benefits such as nutrients or contaminants such as toxic metals and organic pollutants. Current regulations require the periodic monitoring of TDS, which is a measurement of inorganic salts, organic matter and other dissolved materials in water. Measurements of TDS do not differentiate among ions. The amount of TDS in a water sample is measured by filtering the sample through a 2.0 μm pore size filter, evaporating the remaining filtrate and then drying what is left to a constant weight at 180ºC. The concentration and composition of TDS in natural waters is determined by the geology of the drainage, atmospheric precipitation and the water balance (evaporation-precipitation). The mean salinity of the world's rivers is approximately 120 mg L^{-1} and the major anion found in natural waters is bicarbonate. The most commonly occurring cation in fresh water is calcium. Changes in TDS concentrations in natural waters often result from industrial effluent, changes to the water balance (by limiting inflow, by increased water use or increased precipitation), or by salt-water intrusion. It is recommended that different limits for individual ions, rather than TDS, be used for salmonid species. These limits should be based on the effect of the ion on fertilization and egg development.

Key words: Total Dissolved Solid, TDS, water standards, aquatic organisms, Alaska, salmon

INTRODUCTION

Total Dissolved Solid (TDS) is a measurement of inorganic salts, organic matter and other dissolved materials in water[1]. Measurements of TDS do not differentiate among ions. The amount of TDS in a water sample is measured by filtering the sample through a 2.0 μm pore size filter, evaporating the remaining filtrate and then drying what is left to a constant weight at 180ºC[2]. The concentration and composition of TDS in natural waters is determined by the geology of the drainage, atmospheric precipitation and the water balance (evaporation-precipitation)[3]. The mean salinity of the world's rivers is approximately 120 mg L^{-1} and the major anion found in natural waters is bicarbonate, with a mean for all North American river waters of 68 mg L^{-1}[3] The second most common anion is sulfate, with a mean concentration of 20 mg L^{-1}. The most commonly occurring cation in fresh water is calcium, with a mean of all North American river waters for which data were available, of 21 mg L^{-1}; the next most commonly occurring cations are sodium and silica, each with an average concentration of 9 mg L^{-1}[3]. Water with total dissolved solids concentrations greater than 1000 mg L^{-1} is considered to be "brackish". Changes in TDS concentrations in natural waters often result from industrial effluent, changes to the water balance (by limiting inflow, by increased water use or increased precipitation), or by salt-water intrusion.

Total dissolved solids cause toxicity through increases in salinity, changes in the ionic composition of the water and toxicity of individual ions. Increases in salinity have been shown to cause shifts in biotic communities, limit biodiversity, exclude less-tolerant species and cause acute or chronic effects at specific life stages. Bierhuizen and Prepas[4] found a significant and negative correlation between concentrations of chlorophyll-a (an estimate of primary production) and concentrations of Na^{+}, Mg^{2+}, SO_4^{2-}, HCO_3^{-} and CO_3^{2}-. Hallock and Hallock[5] reported substantial changes in marsh communities. When TDS increased from 270 to 1170 mg L^{-1}, both coontail (*Ceratophyllus demersum*) and cattails (*Typha* sp.) were nearly eliminated. Derry *et al*.[6] reported that salinity and aquatic biodiversity are inversely related in lake water.

Changes in the ionic composition of water can exclude some species while promoting population growth of others. For example, Derry *et al*.[6] found that the rotifer *Brachionus plicatilis* and the harpactacoid copepod *Cletocamptus* sp. prevailed in lakes with Cl-

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dominated water. In contrast, the calanoid copepods *Leptodiaptoums sicillis* and *Diaptomus nevadensis* were dominant in the SO_4^{2-}/CO_3^{2-}-dominated lake water. Mount *et al*.[7] stated that the composition of specific ions determined toxicity of elevated TDS in natural waters. In general, they found relative ion toxicity was $K^+ > HCO_3^- = Mg^{2+} > Cl^- > SO_4^{2-}$. Ca^{2+} and Na^+ did not produce significant toxicity. For *C. dubia* and *D. magna*, toxicity of Cl^-, SO_4^{2-} and K^+ were reduced in solutions containing more than one cation.

The diversity of aquatic species decline as osmotic tolerances are exceeded with increasing salinity[6]. Concentrations of specific ions may reach toxic levels for certain species of life history stages. Stekoll *et al*.[8] identified Ca^{2+} as the primary ion responsible for inhibiting hatch of salmonid eggs exposed during fertilization. Erickson *et al*.[9] found that the addition of potassium chloride markedly increased copper toxicity, while addition of calcium chloride and sodium chloride substantially reduced it. Stekoll *et al*.[8] reported that spermatozoa activity was inhibited when small quantities of potassium chloride (19.2 mg L^{-1}) or potassium carbonate (106.2 mg L^{-1}) were added. The current standards of using TDS might be reconsidered to monitor specific ions in light of future risk assessments.

MATERIALS AND METHODS

In order to assess gaps in knowledge and new developments in methodology regarding TDS in Alaska waters, we examined the peer-reviewed literature and official reports to compile available data on toxicity related to TDS. Over forty reports, abstracts and papers were examined which document the effects of elevated TDS on fish spawning and rearing, aquatic invertebrates and aquatic vertebrates. The information is summarized in tables reporting the toxicity of TDS, including the species and life stage tested, the concentration producing the effect and the endpoint. This framework and interpretation of the literature is based on the long experience of the authors.

RESULTS

Invertebrates: Authors have reported a wide range of toxicity (either EC50 or LC50) for aquatic invertebrates, depending on species and especially, on the type of ion (Table 1 and 2). Chapman *et al*.[9] exposed chironomid (*Chironomus tentans*) larvae to two synthetic TDS mixtures modeled after the ionic composition of two mine effluents from Alaskan mining operations. The TDS was primarily $CaSO_4$. They reported significant effects in the chironomid larvae above 1100 mg L^{-1}. Hoke *et al*.[10] reported a 48-h LC50 of 735 mg L^{-1} for *C. dubia* exposed to $NaHCO_3$ and a 48-h LC50 >5000 mg L^{-1} for *Daphnia magna* exposed to NaCl.

Mount *et al*.[7] reported a wide range of toxicities for *C. dubia* and *D. magna*, depending on the ionic composition (Table 1). The researchers reported that mixtures of $KHCO_3 + K_2SO_4$ had the lowest 24-h and 48-h LC50 concentrations for *C. dubia* (390 mg L^{-1} for both 24-h and 48-h). Mixtures of $CaSO_4$ and K_2CO_4 resulted in 24-h LC50 of 1140 mg L^{-1} and 48-h LC50 of 1130 for *C. dubia*. Other mixtures of ions resulted in LC50 concentrations in the range of 2,000 to 4,000 mg L^{-1} and with some mixtures, even higher[7].

Fish: Tests on salmonidae (trout, char, salmon, grayling, whitefish) exposure to high levels of TDS have yielded mixed results, depending upon when exposure occurred[10-14]. Chapman *et al*.[9] exposed embryonic and juvenile rainbow trout (*O. mykiss*) to two synthetic TDS mixtures modeled after the ionic composition of two mine effluents from Alaskan mining operations. No significant effects of the exposures were found on the rainbow trout up to 2000 mg L^{-1}. Their results are consistent with the results of Stekoll *et al*.[8,11] for exposures after fertilization.

Stekoll, *et al*.[15] exposed coho salmon embryos to elevated TDS during different life stages, from post fertilization to button-up fry. They found no significant increase in mortalities with higher concentrations of TDS and concluded that these life stages were unaffected by TDS exposure in either the short or long term. However, when the coho salmon (*O. kisutch*) were exposed at fertilization, higher concentrations resulted in reduced hatch rates and delayed hatch, as well as long-term effects on growth and development. They found coho salmon to be sensitive to TDS exposure at fertilization but not at other embryonic life stages or the juvenile stages from alevin to button- up. Eggs exposed at fertilization that hatched showed effects in later development, i.e., eggs exposed to higher concentrations (1875 and 2500 ppm TDS) had high mortality rates between the eyed and alevin stages. In the 2500-ppm concentration range, they found 50% mortality of the 50% that had been fertilized.

Brix and Grosell[16] conducted similar studies on Dolly Varden (*Salvelinus malma*) and Arctic grayling (*Thymallus arcticus*). They reported an LOEC for Arctic grayling ranging from 254 to >2782 mg L^{-1} TDS and an LOEC for Dolly Varden ranging from >1704 to >1817. Their results for Dolly Varden are similar to the results of Stekoll *et al*.[11] for Arctic char; Stekoll *et al* reported an LOEC of 1875[8]. The wide range in the LOEC for Arctic grayling is possibly related to the ripeness of the fish when eggs and milt were taken.

Table 1: Studies of effects of elevated TDS on freshwater aquatic invertebrates

Species		TDS Components	Effects Unit		Effects Concentration mg L^{-1}	Reference
Chironomus tentans	Diptera larvae	$CaSO_4$	Growth reduced by 45%		2,089	Chapman *et al*.[9]
C. tentans	Diptera larvae	$CaSO_4$	Reduced survival		1,750 and 2,240	Chapman *et al*.[9]
C. tentans	Diptera larvae	$CaSO_4$	10 day, $LC50^1$		2,035	USEPA[22]
C. tentans	Diptera larvae	$CaSO_4$	IC_{20}		1,598	USEPA[23]
Cricotopus trifascia	Diptera larvae	K^+	LC50		1567	Hamilton 1975, cited in ENSR[24]
C. trifascia	Diptera larvae	CL^-	LC50		1406	Hamilton 1975, cited in ENSR[24]
Hexagenia bilineata	Insect: mayfly	K, Li, Mg, Mo, Na, SO_4, NO_3	15 day test, 80% survival		2,270	Woodward *et al*.[25]
H. bilineata	Insect: mayfly	K, Li, Mg, Mo, Na, SO_4, NO_3	30 day test, 70% survival		1,230	Woodward *et al*.[25]
Hydroptila angusta	Insect: caddisfly	K^+	LC50		2316	Hamilton 1975, cited in ENSR[24]
Hydroptila angusta	Insect: caddisfly	Cl^-	LC50		2077	Hamilton 1975, cited in ENSR[24]
Dugesia gonocephala	flatworm	Cl^-	Mortality		1230	Palladina 1980, cited in ENSR[24]
Tubifex tubifex	segmented worm		K^+	$EC50^1$	2000	Khangarot 1991, cited in ENSR[24]
Tubifex tubifex	segmented worm		Ca^{+2}	EC50	814	Khangarot 1991, cited in ENSR[24]
Cyclops abyssorum prealpinus	cyclopoid copepod		Mg^{+2}	EC50	280	Baudoin 1974, cited in ENSR[24]
C.abyssorum prealpinus	cyclopoid copepod		Ca^{+2}	EC50	7000	Baudoin 1974, cited in ENSR[24]
C. dubia	zooplankton			LC50	1,692	Tietge and Hockett[26]
C. dubia	zooplankton		NaCl	48-hr, LC50	835	Hoke *et al*.[10]
C. dubia	zooplankton		NaCl	48-hr, LC50	735	Hoke *et al*.[10]
Cladoceran	zooplankton		$CaSO_4$	LC50, 48-h	>1,910	Mount *et al.* [7]
D. pulex	zooplankton		Ca, ion	EC50, 48-h	499	Goodfellow *et al*.[27]
D. magna	zooplankton			LC50	1,692	Tietge and Hockett[25]
D. magna	zooplankton	<24 h	NaCl	48-hr, LC50	5015	Hoke *et al*.[10]
D. magna	zooplankton	<24 h	NaCl	48-hr, LC50	5000	Hoke *et al*.[10]
D. magna	zooplankton	4th instar	NaCl	48-hr, LC50	4000	Hoke *et al*.[10]
D. magna	zooplankton	<24 h	$NaHCO_3$	48-hr, LC50	1400	Hoke *et al*.[10]
D. magna	zooplankton	<24 h	$NaHCO_3$	48-hr, LC50	1150	Hoke *et al*.[10]
D. magna	zooplankton	7 day	$NaHCO_3$	48-hr, LC50	1780	Hoke *et al*.[10]
D. magna	zooplankton	7 day	$NaHCO_3$	48-hr, LC50	2200	Hoke *et al*.[10]
D. magna	zooplankton	7 day	$NaHCO_3$	48-hr, LC50	1250	Hoke *et al*.[10]
D. magna	zooplankton	<24 h	$NaHCO_3$	48-hr, LC50	1160	Hoke *et al*.[10]
D. magna	zooplankton	<24 h	$NaHCO_3$	48-hr, LC50	1000	Hoke *et al*.[10]
Mysidopsis bahia	mysid shrimp		Ca, ion	LC50, 96-h	927	Goodfellow *et al*.[27]

LC50 = Lethal Concentration 50, or concentration causing 50% mortality
IC0 = Inhibition Concentration 0, or concentration causing inhibition of 0% of the population.
EC50 = Effects Concentration, or concentration effecting 50% of the population.

Ketola *et al*.[12] found that exposing salmonid embryos to high concentrations of calcium (520 mg L^{-1} or greater) during water hardening (post-fertilization) decreased survival rates of several salmonid species. They[12] reported 38% survival at eye up for *Salvelinus fontinalis* exposed to 2229 mg L^{-1} $CaSO_4$, 35% survival

Table 2: Studies of effects of elevated TDS on aquatic plants, algae and bacteria reported in published literature

Species	Effects Concentration mg/L	TDS Components	Effects Unit	Notes	Reference
Algae, species not given	>1400	Not specified		Decline in productivity	Kerekes and Nursall[28] in Sorensen *et al.*[19]
Selanastrum capricornutum	551.3	CaSO4	EC20	All sample concentrations resulted in toxic effects	LeBlond[20]
S. capricornutum	250 – 500			Inhibition of growth	Cleave *et al*. 1976, in Sorensen *et al.*[19]
S. capricornutum	≥2020	$CaCO_4$	Growth inhibition	No toxic effects at 99, 664, 1180, or 1640	EVS Environment Consultants[29]
Nitrogen-fixing bluegreen bacteria	~2450	TDS		Nitrogen fixation limited	Evans and Prepas[22]
Vibrio fischeri	1960	$CaSO_4$	EC20	Inhibited growth	LeBlond and Duffy[21]
Ceratophyllus demersu,	1170			elimination of sensitive species	Hallock and Hallock[5]
Typha sp	1170			elimination of sensitive species	Hallock and Hallock[5]

Table 3: The most toxic ions or combinations of ions identified by Mount et al (1997). Ions are ordered from most toxic to least toxic for each species

Ceriodaphnia dubia	*Daphnia magna*	Fathead minnow
24-h test	24-h test	96-h test
$KHCO_3 + K_2SO_4$	$KHCO_3 + K_2SO_4$	$KHCO_3$
$KHCO_3$ + KCl	$KHCO_3$	K_2SO_4
K_2SO_4 + KCl	KCl	$KHCO_3 + K_2SO_4$
KCl	K_2SO_4 + KCl	$KHCO_3$ +$NaHCO_3$
$KHCO_3$	$KHCO_3$ + KCl	K_2SO_4 + KCl
K_2SO_4	K_2SO_4	$KHCO_3$ + KCl
$MgCl_2 + KHCO_3$		$NaHCO_3$
$KHCO_3 + NaHCO_3$		KCl
$MgSO_4 + KHCO_3$		

for *Salmo solar* exposed to 1395 mg L^{-1} CaCL and 4% survival for *O. mykiss* exposed to 1500 mg L^{-1} $CaSO_4$. In Ketola *et al*.'s study,[12] eggs were dry fertilized (fertilized in the presence of ovarian and seminal fluids only), while embryos in Stekoll *et al*.'s study[11] were fertilized in control or exposure waters. Both studies rinsed fertilized embryos in exposure waters.

Brannock *et al*.[17] examined the individual ionic components of a TDS mixture and the effect of those ions on the fertilization rates of king and pink salmon (*O. gorbuscha*). The ions were tested individually at levels equivalent to Stekoll *et al*.'s 2500-ppm simulation,[11] also at one quarter of the concentration and at four times the concentration. Fertilization rates in both the king and pink salmon were significantly lower with exposure to either calcium or sulfate at 2500 ppm TDS equivalent. Potassium and magnesium ions showed no detectable differences from the control at 2500 ppm TDS equivalent. This work pointed to calcium or possibly sulfates as being the likely cause of lowered fertilization rates.

Mount *et al*.[7] examined the toxicity of different combinations of ions to fathead minnows, in test similar to those conducted with *C. dubia* and *D. magna*. Results with the fathead minnows were similar to results with the invertebrates, producing a wide range of LC50 values, depending on ionic composition. Of the 30 combinations of ions reported by Mount *et al*., one (KHCO3) had a 96-h LC50 <510 mg L^{-1}, 7 combinations resulted in 96-h LC50 concentrations that were less than 1000 mg L^{-1} and a number of ionic combinations resulted in 96-h LC50 values higher than 2000 mg L^{-1}. Mount *et al*.[7] did not test toxicity on reproduction or early development; their tests were limited to mortality of mature fish.

Aquatic plants, algae and bacteria: Few studies were found that documented effects of elevated TDS or of different ions on aquatic plants and algae (Table 2). Kerekes and Nursall (cited in Sorensen *et al*.[18]) found lower productivity in algae at TDS concentrations >1400 mg L^{-1}. LeBlond[19,20] reported an EC20 = 551.3 for *Selanastrum capricornutum.* Evans and Prepas[21] reported decreased nitrogen fixation in bluegreen bacteria exposed to approximately 2450 mg L^{-1} TDS. Hallock and Hallock[5] reported the near elimination of coontail (*Ceratophyllus demersum*) and cattails (*Typha* sp.) in water with 1170 mg L^{-1} TDS.

DISCUSSION

The measurement of TDS integrates all anions and cations in the sample and some ions or combinations of ions are substantially more toxic than other ions or combinations of ions. A species might be more sensitive to TDS toxicity at certain life stages, as many fish are during fertilization. Therefore, a water quality

standard for TDS can take several approaches: 1) The standard can be set low enough to protect all species and life stages exposed to the most toxic ions or combination of ions; 2) The standard can be set to protect most species and life stages for most ions and combinations of ions; or 3) Different limits can be defined for different categories of ions or combinations of ions, with a lower limit during fish spawning, if salmonid species that have been shown to be sensitive to TDS during fertilization and egg development are present.

Approach (1) may be unnecessarily restrictive, although simpler to define and implement. Approach (2), although less restrictive, may lead to adverse effects to aquatic communities. Approach (3) is more complicated to define and would require that the potential discharger determine the composition of the effluent and which species and life stages are present downstream of the effluent. Overall, Approach (3) would provide the greatest protection to aquatic species and the least unnecessary restriction to potential dischargers. The research of Mount *et al*.[7] provides information on toxicity of different ions and ion combinations. Of the ions and combinations of ions tested by Mount, *et al*.,[7] the most toxic to *C. dubia, D. magna and* fathead minnows are shown on Table 3, ordered from most toxic to less toxic. All tests with these ions resulted in LC50 values less than 1,000 mg L^{-1}.

The research of Stekoll *et al*.[11] and Brix and Grosell[17] provide information on toxicity of TDS, mostly in the form of $CaSO_4$, to some Alaska fish species, especially at fertilization. Using the results of Stekoll *et al*.[10] and Brix and Grosell[17] the fish species can be ordered from most sensitive to least sensitive (to $CaSO_4$ TDS): *O. keta (* chum Salmon) > *O. mykiss* (steelhead salmon) > *Thymallus arcticus* (Arctic grayling) > *Salvelinus malma* (Dolly Varden) > *Salvelinus alpinus* (arctic char).

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