



Water Quality

Ambient Water Quality Criteria for Colour in British Columbia: Technical Appendix

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Water Quality Branch
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Summary of Recommended Criteria

Water Use	Parameter	Criterion
Raw drinking water without treatment for colour removal.	True Colour	15 mg/L Pt
Aquatic life, freshwater, estuarine and marine; Wildlife	Apparent Colour	30-day mean transmission of white light shall be less than or equal to 80% of background levels as measured historically or at appropriate reference sites
	True Colour	30-day mean true colour of filtered water samples shall not exceed background levels by >5 mg/L Pt in clearwater systems (background levels less than 20 mg/L Pt) or 20% in coloured systems

		(background levels >20 mg/L Pt)
Livestock watering; Irrigation; and Industrial Water Supplies	True and Apparent Colour	Insufficient information to derive criteria
Recreation and aesthetics, freshwater, estuarine and marine.	Apparent Colour	Secchi disk sighting range less than 1.5 m/
	True Colour	15 mg/L Pt

1. Definitions, Concepts and Analytical Measurements

1.1 Key Concepts

The observed colour of water is the result of light back scattered upward from the water after it has passed through to various depths and undergone selective absorption. Colour and turbidity determine the depth to which light penetrates in water systems. In water, the light intensity or irradiance at a particular depth (I_z) is a function of the intensity at the surface (I_0) to the exponent of the negative extinction coefficient at the depth distance z which is called the Beer-Lambert's Law (Freifelder 1985).

$$I_z = I_0 e^{-\eta z}$$

The extinction coefficient is a constant that predicts the attenuation or dissipation of light at a certain wavelength. In pure water, light is highly absorbed in the infrared region of the light spectrum and poorly absorbed in the blue region. Extinction coefficients are influenced by water absorption, suspended organic and inorganic particles, and dissolved compounds (Jerome *et al.* 1994a; Jerome *et al.* 1994b). Thus, the visible colour in a water sample is the light that is refracted, reflected or re-emitted by substances in water because it has not been absorbed to produce heat or chemical reactions.

The colour of water and other materials has three main attributes: hue, brightness and saturation (Davies-Colley *et al.* 1988). Hue refers to whether the water colour is described as blue, green or yellow, for example, and is determined by the dominant wavelength in the visible spectrum. Brightness depends on the amount of energy detected by the human eye, which is most sensitive to green light of wavelength 555 nm. The saturation depends on the spread of energy around the dominant wavelength. Saturation is also referred to as spectral purity (Jerome *et al.* 1994b).

True colour is due to natural minerals such as ferric hydroxide and dissolved organic substances such as humic or fulvic acids (Hongve and Akesson 1996). A great variety of dissolved organic substances originating from anthropogenic sources such as dyes can also contribute to water colouration (McCrum 1984; Brown 1987; Borgerding and Hites 1994). True colour can only be measured once a sample has been centrifuged or filtered (APHA 1992; Environment Canada 1989; Bennett and Drikas 1993).

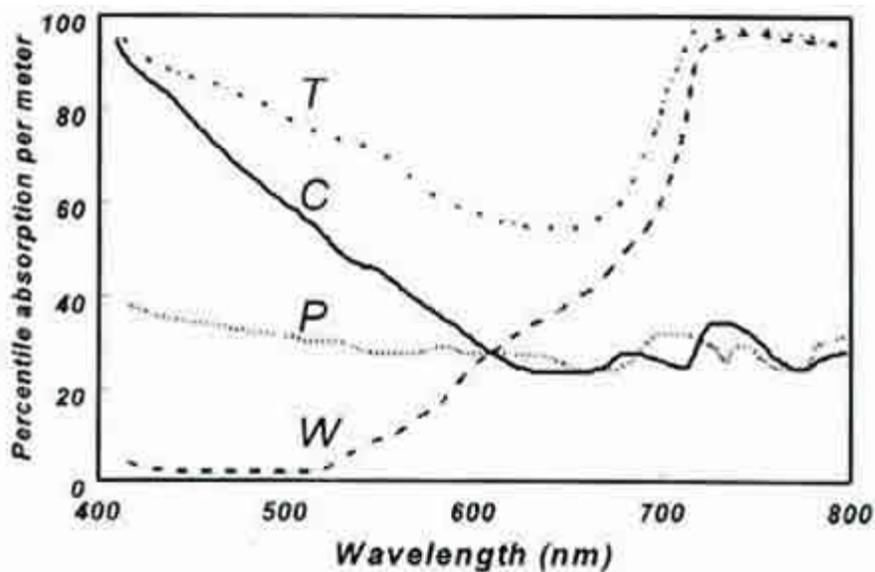
Colour measured in water containing suspended matter is defined as apparent colour (APHA 1992; Bennett and Drikas 1993). Suspended matter can be in the form of large organic particulates such as plant debris, phyto- and zooplankton (Effler and Auer 1987). For example, a blue-green colour can be due to blue-green algal blooms, a yellow-brown colour to diatoms or dinoflagellates, and reds and purples to *Daphnia* or copepods (Chapman 1992). Because some of these organisms thrive on

anthropogenic releases or disturbances (e.g., fertilizers and forest activities), polluted waters may have a strong apparent colour.

1.2 True Colour

The amount of dissolved organic carbon in streams and lakes is typically about ten times the amount of particulate organic carbon. Dissolved organic compounds or "dissolved colour" greatly affects the absorption of light compared to suspended particles. Organic compounds such as humic acids absorb light and reduce its transmission relative to distilled water (James and Birge 1938). As well, the adsorption will be shifted selectively (Figure 1). Organic compounds contributing to the "dissolved colour" are highly selective and marked by UV, blue and green wavelengths and less so in the red and infrared regions of the light spectrum (see curve C, Figure 1). Light absorption by humic acids has been used extensively in the determination of their concentration in water systems (Reckhow and Singer 1990; Mierle and Ingram 1991).

Figure 1. Percentile absorption of light vs. wavelength. T is the apparent colour, C is the true colour, P is that due to suspended particulates and W is pure water. Ultraviolet and infrared wavelengths are <400 nm and >800 nm, respectively.



1.3 Apparent Colour

The extinction coefficient for particulate matter functions independently from that of dissolved organics. Particles in natural waters generally cause a relatively constant attenuation of light through the visible part of the spectrum in spectrophotometric measurements (see curve P, Figure 1), (James and Birge 1938). Jerome *et al.* (1994b) refer to suspended particulates as "white scattering centers" because natural waters with high concentrations of particulates have low spectral purity.

Suspended particulates are a natural component of water systems and can be composed of organic detrital carbon and inorganic suspended sediments, both of which contribute to the absorbance readings. The characteristics and rates of sediment and detrital transport depend on the composition of soils and parent materials, local climatic conditions, topography, hydrology, and vegetation of the watershed (Mitchell and McDonald 1995; Håkanson 1993; Heikkinen 1994; Midgley and Schafer 1992). In addition, land use activities tend to accelerate sediment production, thereby increasing the potential for problematic levels of sediment in the water column (Shields and Sanders 1986; Forsberg 1992). For example, logging can increase the concentration of suspended particulates, especially fine debris coming from terrestrial origin (Bilby and Bisson 1992). Included in this debris is a greater input of carbohydrates and proteins that biodegrade quickly with a consequent increase in primary productivity. Additional production of seston can have dramatic impacts on fish populations.

The type and concentration of suspended matter controls the turbidity and transparency of the water and ultimately the depth of the euphotic zone (*i.e.*, the zone with sufficient light to support photosynthesis, generally one percent of ambient light). Measures of apparent colour by, for example, a measure of transmittance can be used to warn against high/low or increasing/decreasing levels of particulate matter.

1.4 Analytical Methods

True Colour

True colour can be measured by comparator and colourimetric methods. Comparator methods rely on visual comparison of a water sample with a standard colour solution or a set of coloured filter disks. The most common comparator method involves matching a water sample with one of a series of dilutions of a standard colour solution of platinum and cobalt chloride salts of molar ratio 2:1 where the platinum concentration in mg/L is equivalent to the colour value in Hazen units (Bennett and Drikas 1993). The Fore-Ule colour scale involves comparisons to alkaline solutions of cupric sulfate, potassium chromate and cobaltous sulfate. The Hazen scale of true colour measurement, however, has been adopted as the reference method by organizations that set standards for water quality analysis, and by many governments in deriving their drinking water quality guidelines (APHA 1992; NH & MRC and AWRC 1987; WHO 1983; EN-ISO 1994).

Colourimetric methods are based on the calibration of absorbance of the water sample at a variety of single wavelengths, usually against the Pt-Co standard (Bennett and Drikas 1993; Hongve and Akesson 1996). Standard measurement comparisons can be made with sealed containers (*e.g.*, the *Hellige Aqua Tester*). Natural waters range from <5 in very clear waters to 1200 mg/L Pt in dark peaty waters (Kullberg 1992). As some of the compounds determining the colour of water are not very stable, measurements should be made within two hours of collection (Environment Canada 1989).

Comparator or visual assessment methods are not very precise. Most operators find it difficult to distinguish between colours that differ by <5 mg/L Pt (Hongve and Akesson 1996). Inter-laboratory comparisons of colour generally produce a standard deviation of approximately 5 to 10 mg/L Pt (Bennett and Drikas 1993; Hongve and Akesson 1996). Given the drinking water standard in Canada of 15 mg/L Pt (Health Canada 1996), the coefficient of variation for maximum permitted colour is between 33 and 67%. Such uncertainty has necessitated the development of a non-visual, more precise means of quantifying true colour as calibrated against the Hazen scale. A major obstacle, however, has been to match apparatus readings with visual judgments because photometers are confined to measures at defined spectral lines or bands (Hongve and Akesson 1996). The turbidity of natural waters also interferes with the measurement of true absorbance because spectrophotometers are not designed to measure the scattering of light (Bennett and Drikas 1993). Therefore, several steps are required before there can be good agreement between comparator and colourimetric methods. First, turbidity must be removed by either filtration or centrifugation (APHA 1992), or its contribution quantified (Bennett and Drikas 1993; Hongve and Akesson 1996). The common practice of filtration through 0.45 micron filters should be satisfactory for most waters, although repeated filtration may be required for very turbid waters. Bennett and Drikas (1993) found that turbidity is a linear function of absorbance at selected wavelengths between 350 and 700 nm (also see Figure 1, line P). Using this information, they were able to derive the following equation that corrects for turbidity in photometric determinations of true colour (**C**) in mg/L Pt:

$$C = \frac{l}{\epsilon \cdot \left[\left(\frac{A}{l} \right) - E \cdot t \right]}$$

where ϵ is the colour absorptivity (mg/L Pt/cm), **E** is the coefficient of scattering (NTU/cm), **t** is turbidity (NTU), **A** (in proportion) is total absorbance due to dissolved coloured species, and **l** corresponds to cell path length (cm). Note, however, that the correction for turbidity assumes that particle size distribution in water samples, an inherently variable characteristic in natural waters, is similar to that of the kaolin suspension used in the calibration experiment. Although correction for turbidity would be useful in approximating true colour, it cannot be reliably applied to all waters.

Once turbidity has been removed or quantified, the next step is to select the appropriate wavelength for measuring true colour. In order to produce general agreement with comparator methods, the appropriate wavelength should exhibit equal absorbance when comparing natural coloured waters and the Pt-Co reference solution. For natural waters with high concentrations of humic and fulvic acids, this occurs around 410 nm, and 445-470 nm. The shorter wavelength has better sensitivity and one inter-laboratory comparison between Nordic countries and two inter-laboratory comparisons in Norway have shown that photometer readings at 410 nm and comparator readings gave identical results, with the former method having much better precision (Hongve and Akesson 1996). Bennett and Drikas (1993); however, recommend single wavelength analysis at 456 nm because the influence of turbidity (after filtration) is negligible at this wavelength (see Figure 1). Note that both comparator and colourimetric methods based on the Hazen scale are not appropriate for industrial or other wastewaters that diverge in colour from the Pt-Co standard. Coloured compounds in wastewaters and humic and fulvic acids have different absorption spectra and thus will not exhibit equal absorbance at the same wavelengths as occurs with humic and fulvic acids and Pt-Co reference solutions at 410 nm and 445-470 nm. Several of the methods discussed below are more appropriate for wastewaters.

Crowther and Evans (1981) suggested that analysis across a broad analytical wavelength range (405 to 460 nm) produces colour readings in good agreement with comparator methods. Similar good agreement has been achieved in the analytical wavelength range 445 to 470 nm by Bennett and Drikas (1993). The latter authors argue; however, that the improvement of broad wavelength analysis over single wavelength analysis is marginal with the former method requiring much additional effort.

Colour is dependent on factors that affect the solubility and stability of the dissolved and particulate fractions of the sample such as pH, temperature, exposure to light, and storage time. Although most methods recommend measurement and recording of pH, pH standardization is not desirable because the resultant colour will differ from the colour of water *in situ* (Bennett and Drikas 1993). Also, to ensure that sample and *in situ* water colour are the same, most methods recommend that colour samples be analyzed within two hours (Environment Canada 1989).

A specialized method, derivative spectroscopy, can be used to help identify sources of pollution in water samples contaminated by coloured substances (McCrum 1984). Derivative spectroscopy in the UV-visible region of the spectrum records variations in the rate of change of absorbance (**A**) with wavelength. Thus, in the first order derivative spectrum **dA/dwavelength** is plotted against wavelength, in the second order derivative spectrum **d²A/dwavelength²** is plotted against wavelength and so on for higher order derivative spectra. The most useful characteristic of derivative spectroscopy is the increase in resolution and detail produced. In water analysis, derivative spectroscopy has been applied to the quantitative determination of phenol in wastewater, uric acid in municipal wastewater, nitrate and nitrite in water, and to investigate suspected sources of colour in natural waters (McCrum 1984).

Apparent Colour

Apparent colour is due to dissolved organic matter and suspended particulates in the water such as plant debris, phyto- and zooplankton (Effler and Auer 1987). Despite suspended particulates having relatively non-selective scattering properties, high concentrations of particulate matter of inorganic clays or volcanic ash can produce a yellow to red colour, while high concentrations of blue-green algae and diatoms produce blue-green and yellowish-brown colours, respectively (Wetzel 1975).

Since the absorption spectrum of particulate matter is relatively non-specific, some measures of apparent colour simply estimate the reduction in light transmission or visual clarity resulting from scattering of light by particulates. The most common method for estimating visual clarity is the Secchi disk method. The Secchi disk transparency is the mean depth of the point where a weighted white disk, 20 cm in diameter, disappears when viewed from the shaded side of a vessel during mid-day, and the point where it reappears upon raising it after being lowered beyond visibility (Wetzel 1975). The Secchi disk transparency is a function of the reflection of light from its surface and is therefore influenced by both the absorption characteristics of the water and the presence of dissolved and particulate matter. Most studies indicate, however, that particulate matter influences Secchi disk transparency to a greater extent than does true colour (Wetzel 1975). For example, multiple regression of data from 55 Florida lakes yielded the following close-fitting equation ($r^2 = 0.89$), (Brezonik 1978):

$$SD^{-1} = 0.106 + 0.128 \cdot T + 0.0025 \cdot C$$

where **SD** is Secchi disk transparency in meters, **T** is turbidity in nephelometric turbidity units (NTU) and **C** is true colour in mg/L Pt. When only one independent variable was included in the regression equations, the r^2 value for turbidity was 0.71 and for colour it was 0.10, indicating that both variables contribute to Secchi disk transparency, although turbidity is considerably more important. In these lakes, turbidity was primarily autochthonous and thus closely related to number of algal particles.

An alternative method for measuring visual clarity relies on a black disc viewed horizontally in the water using a right-angle viewer (Davies-Colley and Smith 1992). The black disc method can be used in shallow waters where the Secchi disk cannot be used. The black disc sighting range is inversely proportional to the beam attenuation coefficient, and can be used to estimate this optical property of water (Davies-Colley and Smith 1992). The method is routinely used in water resources investigations and management programs in New Zealand, and may eventually replace the Secchi disk method (Davies-Colley and Smith 1992; Smith *et al.* 1991; Smith *et al.* 1995). Davies-Colley and Smith (1992) describe the black disc method, including several adaptations that may be used when *in situ* measurements are difficult, or for very turbid waters.

A robust means of determining *in situ* apparent colour is the Munsell system of colour (Davies-Colley *et al.* 1988). The Pt-Co scale refers only to the yellowness of filtered water samples and does not cope well with blue or green-hued waters. The Munsell system does not have this shortcoming. The system has three coordinates: Munsell hue (H), value (V), and chroma (C). Munsell hues are divided into 100 hue units and are designated as, for example, 10 BG indicating that the sample corresponds to the 10th unit of the blue-green hue range. The Munsell value is a measure of apparent brightness and ranges from 0 (black) to 10 (white). The Munsell chroma is related to colour saturation (or spectral purity) and extends from 0 for neutral grays to values of 20 or more for the most saturated colours. Munsell scores are designated by a notation indicating hue, value and chroma in H V/C format. For example, a bright, low saturation green might be 8.5 G 7/4. Munsell standards are available in a convenient book form that is readily transportable. Although the Munsell system of colour is a comparator method and suffers from some of its shortcomings, the technique shows good correspondence to the results of chromaticity analyses applied to spectro-radiometric scans of near-surface upwelling light in a diverse range of New Zealand lakes (Davies-Colley *et al.* 1988). Munsell hue is routinely measured in water quality surveys in New Zealand (Davies-Colley and Smith 1992; Smith and Davies-Colley 1992; Smith *et al.* 1991) and elsewhere (Eloranta 1978).

The tristimulus colour system is based on a system of parameters referred to as tristimulus values that can be calculated from up- and down-welling spectral irradiance data (Thomson and Jerome 1975). These parameters plotted on a CIE chromaticity chart numerically define the colour of a particular irradiance measurement in terms of a dominant wavelength and its purity or monochromaticity (Thomson and Jerome 1975; Davies-Colley *et al.* 1988; Jerome *et al.* 1994a,b). The tristimulus colour system implies that the dominant wavelength is composed of a combination of three colours: red, blue and green. The tristimulus values of an upwelling irradiance spectrum $E(\text{wavelength})$ are given by:

$$X' = \int E(\lambda)x(\lambda)d\lambda$$

$$Y' = \int E(\lambda)y(\lambda)d\lambda$$

$$Z' = \int E(\lambda)z(\lambda)d\lambda$$

where $x(\text{wavelength})$, $y(\text{wavelength})$ and $z(\text{wavelength})$ are the CIE colour mixtures for red, green and blue, respectively for equal energy spectra. These may be obtained from CIE tables (Jerlov 1976). The

chromaticity coordinates X, Y and Z for red, green and blue, respectively are then obtained from the equations:

$$X = \frac{X'}{X' + Y' + Z'}$$
$$Y = \frac{Y'}{X' + Y' + Z'}$$
$$Z = \frac{Z'}{X' + Y' + Z'}$$

Since $X+Y+Z = 1$, two chromaticity coordinates adequately represent a chromaticity diagram. The loci of all possible (Z,Y) pairs define an envelope which encompasses all possible chromaticity values. For a white spectrum, $X = Y = Z = 0.333$. This defines the achromatic point S. The dominant wavelength of a particular measured spectrum C is determined by the intersection of the line S-C with the chromaticity envelope indicated by point L. The dominant wavelength is the colourimetric definition of colour in the water body. The spectral purity of the dominant wavelength is defined as the ratio of the line C-S to the line L-S. Thus, spectral purity is a measure of the contribution of the dominant wavelength to the observed optical spectrum (Jerome *et al.* 1994a,b). A value of 1.0 indicates a monochromatic spectrum at the dominant wavelength, while a value of 0 indicates a white spectrum. The tristimulus colour system is a standard method (APHA 1992) and, although more complicated than the Hazen system, can be applied to a broader range of coloured waters such as industrial wastewaters containing high concentrations of dyes. The tristimulus system can also distinguish between waters with varying amounts of particulate matter (Thomson and Jerome 1975; Jerome *et al.* 1994a,b). For example, in studies of near-surface upwelling irradiance in Lakes Ontario and Superior, clear waters had a dominant wavelength of 490-530 nm, biologically productive waters had a dominant wavelength of 550-560 nm, and waters with heavy sediment loadings had a dominant wavelength of >565 nm (Thomson and Jerome 1975). This relationship has been noted in other studies (Davies-Colley *et al.* 1988; Bukata *et al.* 1983; Jerome *et al.* 1994a,b; McPherson and Miller 1987).

2. Occurrence

2.1 Natural Sources

The natural colouration of aquatic systems can be pleasing to the eye. Humans associate pristine systems with deep blues or the turquoise colour seen, for example, in glacial lakes. Colloidal CaCO_3 scatters light in the greens and blues to give these lakes their characteristic colour. Forest streams often appear very dark or brownish-yellow. For example, the relatively undisturbed Yacoun River and its tributaries on Graham Island, British Columbia have a true colour varying from 13 to 922 true colour units (TCU), (Nijman 1993). This is due to the allochthonous inputs into the system composed of, for example, humic/fulvic acids, phenols, tannins and, saponins (Nijman 1993; also Midgley and Schafer 1992). These can form organo-metal (iron/aluminum) complexes responsible for staining of water (Mitchell 1990). Water may take on a seston colour that, if anoxic, harbours cyanophytic bacteria imparting a blue-green appearance to the water. In aerated waters, algal or bacterial blooms may occur that cause a green or red colouration.

Colouration of an aquatic system depends on many factors some of which are in flux or in a continuous state of dynamic equilibrium. For example, heavy rains will enable the transport of organic material, nutrients and minerals into aquatic systems. Colour values increase with increasing dissolved organic matter concentrations (Heikkinen 1994). Lake turnover will re-suspend organic material making it available for primary productivity and seston colour. If lakes are associated with wetlands, these will increase the colouration of lakes. For example, Seymour Lake in the interior of British Columbia is more highly coloured (mean = 50 TCU) than several nearby lakes (means = 8.3-20 TCU) likely because it is a bog lake (Boyd *et al.* 1985). The breakdown of vegetative matter, particularly *Sphagnum* (peat moss), releases dissolved tannins and lignins into the water causing a brown colouration. Wet meadows or herbaceous, seasonally-flooded wetlands contribute more to lake water colour than do cattail marshes (Detenbeck *et al.* 1993).

Studies of aquatic systems in British Columbia have shown that apparent colour is often closely matched to seasonal flow patterns. Annual freshets, for example, can cause marked increases in turbidity and reductions in water clarity, particularly in glacier-fed streams (*e.g.*, Webber 1996a,b,c; Wiperman and Webber 1996). As a result, seasonal variations in apparent colour in British Columbia aquatic systems can be dramatic. For example, apparent colour in the Salmon River at Hyder was shown to range from the detection limit of 5 TCU to a maximum of 160 TCU during the period 1982 to 1995 (Webber 1996c).

Figure 2 is a schematic illustration of the possible mechanisms that have an influence on the colour of an aquatic system. Lake colour in Figure 2 is a function of allochthonous inputs, autochthonous production and re-suspension or internal loading (Häkanson 1993). These factors are in turn linked to physical, chemical and biological features of the drainage area and of the lake. A similar scenario could be used for aquatic systems other than lakes. The Figure indicates some of the complexities in the determination of the natural sources of colour in aquatic systems.

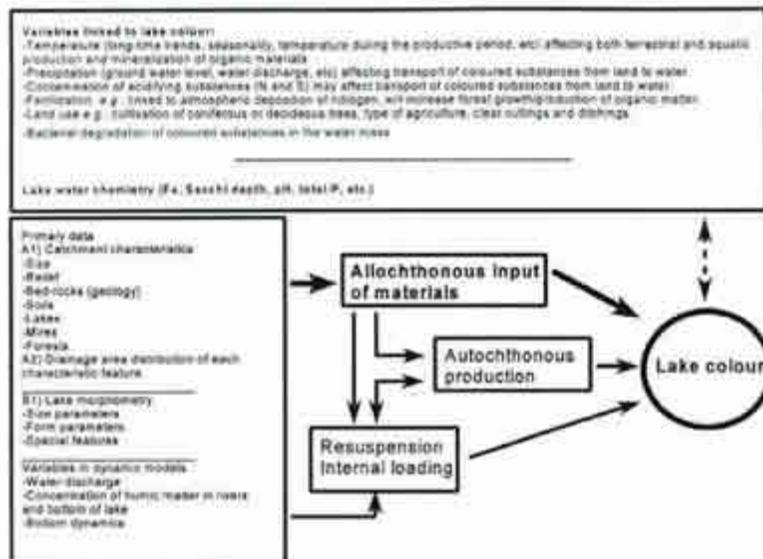
2.2 Anthropogenic

Anthropogenic activities can have a profound effect on the colour of aquatic systems (Parker and Sibert 1976; Shields and Sanders 1986; Mitchell and McDonald 1995; Weis *et al.* 1989). Of perhaps greatest concern in British Columbia, are forest management practices (Hatfield Consultants Ltd. 1994; Butcher 1992; Taylor 1994; Nordin and Holmes 1992). Forest management practices can cause increases in water colour as a result of increased soil erosion due to construction of infrastructure and harvesting of trees, discharge of highly coloured effluents, and leaching of wood debris, both *in situ* and from nearby storage sites (Butcher 1992; Taylor 1994; Nordin and Holmes 1992; Forsberg 1992).

Figure 3 illustrates the profound influence that discharges of coloured effluent from pulp mills can have on ambient water colour, even in relatively large rivers such as the Fraser River. In September, 1986, true colour immediately downstream of the Northwood Pulp and Timber diffuser at Prince George on the Fraser River was 45 TCU compared to upstream values of 5 TCU (Hatfield Consultants 1994). At 4.7 km downstream, true colour had decreased to 15 TCU. Values immediately downstream of the Canadian Forest Products at Prince George diffuser increased to 105 TCU and remained elevated (65 TCU) 5.6 km downstream. Aerial photographs clearly show that the colour component of the effluents from these kraft mills persists for at least 2 km downstream of their diffusers.

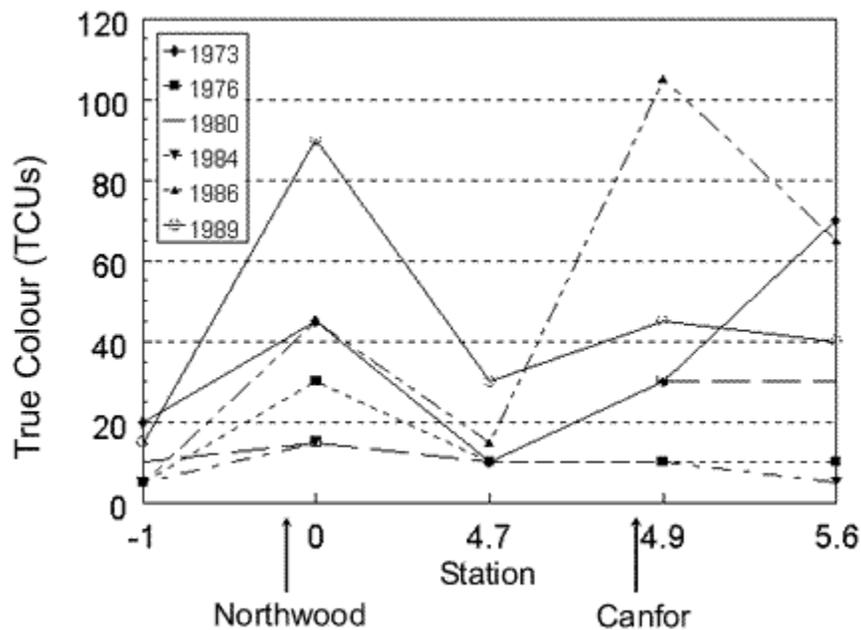
The Weyerhaeuser pulp mill has been shown to cause a dramatic increase in water colour in the Thompson River between the confluence of the north and south sections of the river and Kamloops Lake (Nordin and Holmes 1992). The effluent from the mill is brown and often has monthly mean values for true colour of 2000 SWU or higher. Public concern over colour has been expressed for the lower Thompson River.

Figure 2. Schematic illustration of variables accounting for colour in an aquatic system (adapted from Håkanson 1993)



since the early 1970s, and led to a colour reduction program by Weyerhaeuser beginning in 1980. Despite the reduction program, the available data indicate a fairly consistent increase in mean colour values during the low flow period of 2 to 7 SWU between upstream and downstream stations (North and South Thompson in comparison with Savona or Walhachin).

Figure 3. True Colour (TCUs) Chart



Another mill causing serious increases in water colour in British Columbia is the Celgar Mill on the Lower Columbia River (Butcher 1992). Local residents prefer not to swim between Celgar and Castlegar because of the discolouration of water from Celgar's effluent discharge. The Celgar effluent has a dark brown colour (750 - 2360 TCU during 1988 to 1990) that originates in the separated lignin fraction, especially the humates that combine with the extracted tannins. Data from 1983 and 1984 indicate that downstream true colour values (to Kootenay River confluence) ranged from 9 to 58 SWU compared to upstream values of <5 SWU. Celgar is currently undergoing a plant modernization that is predicted to reduce effluent colour by 62%. Even with this reduction, the colour increase in the Columbia River is expected to be 18 TCU in winter and 16 TCU in summer at the edge of the initial dilution zone. Sunken log debris near the Celgar woodroom also causes a darkening of water colour due to release of organic constituents from the wood (see also Lan *et al.* 1995).

In northern British Columbia, dark leachates from woodpiles of trembling aspen have been observed. A field study by Taylor (1994) revealed that the leachate initially had a dark amber colour that darkened further with age as a result of decomposition of the organic component (overall range = 220 to 1550 SWU). Given the large quantities of aspen currently harvested (500,000 m³/year) and stored in the open in British Columbia, there is the potential that this source could significantly augment true colour of nearby aquatic systems.

Other sources of dissolved contaminants in British Columbia and elsewhere could include, for example, surfactants, dyes, and wood preservation chemicals all of which could potentially be contributing to colour in aquatic systems. Surfactants are used in a wide variety of products including pesticide formulations, paints and detergents. These chemicals are not under regulation because they are considered to be "inerts" and are difficult to analyze. They absorb strongly in the blue colour range and can contribute to colour measurements as a result.

Dyes are water soluble or water dispersible organic substances used by the colourant industry (Brown 1987). There are potentially thousands of products that contain dyestuffs and although the probability of most of these getting into aquatic systems is very low, some can be detected in aquatic systems. In areas outside of British Columbia, triphenylmethane blue (acid blue toilet flush), has been found in rivers at a concentration of 1.7 g/L (Richardson and Waggott 1981) and food and cosmetic dyes (acid blue 9, acid violet 17, Quinoline yellow, acid red 51, 87 and 92, and *N*-benzyl-*N*-ethylaniline sulfonic acid) were found in wastewater treatment plants in the mg/L concentration range (Borgerding and Hites 1994).

Of considerable importance are the wood preservation facilities in British Columbia. Compounds used in heavy duty wood preservation such as copper chromated arsenicals and those used as anti-sapstains (TCMTB) are highly toxic to aquatic life and contribute to the colouration of water.

3. Drinking Water

3.1 Water Treatment

The major mechanism for removal of dissolved coloured substances such as humic and fulvic acids is the coagulation/sedimentation process (National Health and Welfare 1993). In British Columbia, very few water purveyors apply treatment more than disinfection. Organics removal by coagulation has been found to be optimal at pH 4 to 6. Removal of organic material by aluminum and iron salts is effective with removal efficiencies varying from 55 to 90% between source waters (Reckhow and Singer 1990). In order to prevent the formation of trihalomethanes (THMs), the initial point of chlorine application should follow the coagulation/sedimentation process; reductions in THM production of up to 75% have been reported by such a change in process (National Health and Welfare 1993). Oxidation of THM precursors by chemical oxidants other than chlorine (e.g., hydrogen peroxide, ozone, UV radiation) are possible methods of THM control. Alternatively, disinfecting agents other than chlorine may be used to avoid the formation of THMs. Removal of THM precursors by activated carbon has had limited success because of early breakthrough problems (Symons *et al.* 1982). Special treatment for THM control after formation usually involves air stripping and adsorption (Symons *et al.* 1982). Note that the removal of other colouring agents such as iron, copper, surfactants and dyes may require different treatment techniques. For example, iron removal usually consists of oxidation by chlorine, potassium permanganate or ozone followed by liquid/solid separation (National Health and Welfare 1993).

Suspended particulates that contribute to apparent colour are generally removed during the pre-treatment step usually by a combination of coarse and fine screens, micro-strainers and/or simple gravity settling (National Health and Welfare 1993).

3.2 Effects

Few toxicity studies of colouring agents such as humic and fulvic acids have been undertaken. The few studies that have been conducted indicate that organic colouring agents are not toxic at the levels that could occur in drinking water. For example, male rats supplied with soil fulvic acid for up to 90 days at levels of 10, 100 and 1000 mg/L showed no significant changes in body weight, intake rates, organ/body weight ratios or tissue histology (Health Canada 1996). Little information is available on the toxicities of metals and their humate complexes (Health Canada 1996).

Limits for colour in drinking water are generally based on aesthetic considerations. Research into perception of water quality tends to support the view that the public uses many factors in judging water quality, but that visual factors predominate. In particular, consumers find water with low clarity or a yellowish hue to be objectionable (Smith and Davies-Colley 1992; Smith *et al.* 1991). Levels of colour above 15 mg/L Pt in a glass of water can be detected by most people (Health Canada 1996).

Although colour *per se* represents an aesthetic problem in water supplies, potential harm to humans can arise due to the reaction between humic and fulvic acids and chlorine to form THMs, trichloroacetic acid, dichloroacetic acid, halo ketones and haloacetonitriles (Reckhow and Singer 1990; Rook 1977). Many of these compounds are probable carcinogens to humans or have been shown to be mutagenic (Health Canada 1996; Reckhow and Singer 1990). Reckhow and Singer (1990) observed that the average yield of THMs in drinking waters of seven US cities was 52.2 g/mg total organic carbon. In cities with high organic carbon concentrations in the raw water (greater than or equal to 15 mg/L), concentrations of THMs were observed in the low mg/L range (Reckhow and Singer 1990).

3.3 Literature Criteria

Most countries have established criteria for true colour in drinking water based on aesthetic considerations using the Hazen scale. For example, the true colour criterion derived by Health Canada, Quebec, Australia and the World Health Organization is 15 mg/L Pt because this is the level at which most people can detect colour in a glass of water (Ministere de l'environnement du Quebec 1992; WHO 1983; Health Canada 1996; NH & MRC and AWRC 1987; Australia 1992). Most countries recommended criteria for turbidity and suspended solids to protect drinking water from the constituents of apparent colour. No criteria for apparent colour to protect drinking water were found in the world literature.

3.4 Proposed Criteria

The aesthetic water quality criterion for true colour is 15 mg/L Pt. This criterion should not be exceeded at any time, but only applies to systems in which background colour is less than 15 mg/L Pt and the water does not require treatment beyond disinfection.

3.5 Rationale

The criterion for true colour is set at 15 mg/L Pt to ensure that consumers whose drinking water is aesthetically unpleasing do not seek alternative, possibly unsafe, sources of drinking water. It also recognizes that most water purveyors in British Columbia do not treat water supplies beyond disinfection. The provision of drinking water at or below this limit will also guard against interferences by colour in treatment water processes and analytical procedures (Health Canada 1996). The removal of excess colour prior to chlorination will also reduce the production of THMs and other substances that complex to humates at low levels. Given that criteria for turbidity and suspended solids are a better means to address inputs of suspended matter that cause coloration of water supplies and that where available

drinking water treatment effectively removes suspended particulates, no criterion for apparent colour is required.

4. Aquatic Life

4.1 Effects

The presence of coloured substances in aquatic systems has been associated with changes in primary productivity (Ilmavirta and Huttunen 1989; Arvola 1986; Del Giorgio and Peters 1994; Henebry and Cairns 1984; Haynes et al. 1994), depth of the euphotic zone (Eloranta 1978), phytoplankton species composition (Sheath et al. 1986; Vegas-Vilarrubia 1995; Ilmavirta and Huttunen 1989; Beauchamp and Kerekes 1989), protozoan colonization rates (Henebry and Cairns 1984), secondary production (Hessen 1985), macro-invertebrate behaviour (Juarez et al. 1987), and macro-invertebrate community structure (Kullberg 1992). Colour can also alter the availability and hence toxicity of heavy metals to fish (Nilsson and Håkanson 1992; Haines et al. 1995; Nilssen 1982; Hutchinson and Sprague 1987). The effects of colour on aquatic biota are discussed in the following sections.

4.1.1 Bacteria

Several studies have noted that brown-water systems with high concentrations of dissolved humics are associated with increased bacterial productivity (Hessen 1985; Tranvik *et al.* 1991). For example, Hessen (1985) observed that the mean annual biomass of bacteria in holarctic oligotrophic lakes was 7.8-12.1 g C/L in clear lakes, 10.5 g C/L in slightly coloured lakes and 16.2-44.1 g C/L in highly coloured humic lakes (note that colour was not quantified in the humic lakes). Bacterial and zooplankton biomass were also high relative to algal biomass, strongly supporting the possibility that humics are an essential component of the carbon pool in these systems. Similarly, Tranvik *et al.* (1991) observed a significant correlation between bacterial abundance in 23 oligotrophic lakes in southern Sweden and water colour (Spearman rank correlation, $r_s = 0.62$). Bacterial abundance in the highly coloured lakes (colour = 180 mg/L Pt) was approximately double that observed in clearwater lakes (colour = 5 to 20 mg/L Pt). It should be noted that some anthropogenic coloured substances such as textile dyes may cause reductions in bacterial biomass, although such effects are likely due to chemical toxicity rather than to changes in the optical properties of the water (Tratnyek *et al.* 1994).

4.1.2 Aquatic Plants

The amount of photosynthetically active radiation in natural waters is of fundamental importance in determining the productivity of vascular plants and phytoplankton. Absorption and scattering by water and dissolved and particulate matter determine the quantity and spectral quality of light at a given depth, which in turn affect the photosynthesis of primary producers. The following discussion relates the effects of colour to primary producers in freshwater and estuarine and marine systems.

Freshwater

Numerous studies have demonstrated a strong positive correlation between primary production and water colour in freshwater lakes and rivers (Del Giorgio and Peters 1994; Ilmavirta and Huttunen 1989; Arvola 1986; Henebry and Cairns 1984). This correlation exists in spite of the smaller euphotic zone that

characterizes highly coloured aquatic systems (Del Giorgio and Peters 1994; Ilmavirta and Huttunen 1989; Eloranta 1978). Eloranta (1978), for example, found that the euphotic zone in freshwater lakes in Finland decreased from 10 m to 4-5 m with an increase in colour from 5 to 20 mg/L Pt. Several factors could explain this apparent anomaly. First, most measures of annual productivity are confined to the euphotic zone or epilimnion. Productivity of benthic and periphytic algae would likely be higher in clearwater systems. Second, water colour is often positively correlated with nutrients such as total phosphorus and nitrogen (Del Giorgio and Peters 1994; Ilmavirta and Huttunen 1989; Henebry and Cairns 1984); high concentrations of nutrients have a profound effect on primary productivity, perhaps sufficient to override the reduced light penetration in highly coloured systems. Other possible factors contributing to the positive relationship between water colour and primary production include (i) zooplankton grazing on phytoplankton will be more effective in well illuminated water (Ilmavirta and Huttunen 1989), and (ii) humic acids in highly coloured, low pH systems act as a weak buffer and can therefore reduce the effect of acid deposition on primary production (Kullberg 1992).

A more direct means of ascertaining the effects of water colour, both true and apparent, is to examine how changes in water colour affect primary producers while other variables (*e.g.*, nutrient concentrations) are held constant. Carpenter *et al.* (1996) observed that artificially splitting Long Lake in Wisconsin into two basins led to a three-fold increase in water colour in the east basin, while little change occurred in the west basin. The change in water colour was likely the result of a two-fold increase in dissolved organic matter. The increased water colour in the east basin led to a shift in the vertical distribution of phytoplankton such that the proportion of chlorophyll *a* in the metalimnion was approximately 0.32 in this basin, compared to 0.62 in the west basin (Christensen *et al.* 1996). This change was accompanied by a reduction in the depth of oxygenation in the east basin.

In addition to the effects on primary productivity, water colour can also affect species composition (Arvola 1986; Ilmavirta and Huttunen 1989; Vegas-Vilarrubia 1995; Sheath *et al.* 1986). This is expected since algal absorption spectra, and hence photosynthetic efficiency at various wavelengths, differ markedly among algal groups according to the amounts of accessory pigments accompanying chlorophyll *a* (Atlas and Bannister 1980). Also, zooplankton grazing will be effective at eliminating large, non-motile algae in clearwater systems, but less so in coloured systems (Ilmavirta and Huttunen 1989). Ilmavirta and Huttunen (1989) found that humic-stained lakes (median colour = 150 mg/L Pt) in Finland tended to have larger populations of blue-green algae (which can increase the concentration of the phycocyanin pigment when grown in water with a dominant wavelength in the red portion of the spectrum), motile flagellates (which are efficient at finding optimum light intensities and spectra), and overall higher species richness than did clear lakes (median colour = 5 mg/L Pt). Sheath *et al.* (1986) also found that a blue-green alga, *Phormidium retzii*, dominates lowland, brown-water streams in south-central Alaska (colour not quantified), while the chrysophyte, *Hydrurus foetidus*, dominates clearwater streams, the latter of which also has lower species richness.

Estuarine and Marine Waters

Few studies have quantified the effects of colour on estuarine and marine primary producers. Estuaries are often enriched with plant nutrients compared with offshore waters because of inputs from the surrounding landscape. When nutrients are abundant, phytoplankton populations may flourish in the upper waters and cause shading of benthic algae and sea-grasses (Orth and Moore 1983). Reduced light availability has been implicated in the decline of sea-grasses and submerged vegetation in several

of Florida's largest estuaries including Charlotte Harbour, Tampa Bay and Indian River lagoon (Orth and Moore 1983; Gallegos and Kenworthy 1996). In Charlotte Harbour, seagrass coverage was reduced by 29% between 1945 and 1982. Light attenuation is particularly high in the northern half of this estuary as a result of basin runoff and inflows from tidal rivers (Arvola 1986). In this area, dissolved matter caused a reduction in the amount of photosynthetically active radiation (PAR), such that much of the bottom was below the depth of 1% surface light. Not only was PAR reduced, but the spectral distribution shifted such that the shorter wavelengths (400-500 nm) were effectively eliminated in the first few centimeters of water in highly coloured waters (greater than or equal to 25 mg/L Pt). This is the part of the spectrum that higher plants such as sea-grasses use most effectively in photosynthesis. Dissolved matter had little effect on light attenuation in much of the southern part of the estuary (colour <5 mg/L Pt), where seagrass coverage is much more extensive. Several studies have indicated that the deep edges of seagrass beds extend to depths at which approximately 20% of surface irradiance penetrates (Gallegos and Kenworthy 1996). When turbidity is low (<2 NTU), a modest colour change from 5 to 7.9 mg/L Pt can decrease the lower limit of the seagrass bed from 2 m to between 1.25 and 1.5 m (Arvola 1986).

A laboratory investigation of the effects of coloured Lake Coleman solution surrounding growth tubes with the estuarine diatom *Phaeodactylum tricornutum* indicated a strong negative relationship between water colour and cell density (Haynes *et al.* 1994). The source of colour to Lake Coleman (Australia) were pulp and paper mill, domestic and industrial effluents. Isolating the growth tubes from the coloured solution was required to eliminate the effects of nutrients and other water quality variables. The resulting regression equation was:

$$\log_{10}CD = 2.31 - 0.0018Col$$

where **CD** is algal cell density (x10,000/mL) and **Col** is colour measured as mg/L Pt. Using this equation, a change in water colour from 10 to 50 mg/L Pt would cause a 15.3% reduction in algal cell density. Coloured pulp and paper mill effluents have also been found to reduce algal productivity in areas with poor flushing along the British Columbia coast. Parker and Sibert (1976) found that a humic-stained effluent with a colour of 1000 mg/L Pt discharged from a British Columbia mill to upper water layers prevented photosynthesis in sub-halocline phytoplankton at the head of Alberni inlet.

4.1.3 Invertebrates

Many invertebrate species possess visual receptors with peaks that correspond to the spectral quality of their preferred habitats. For example the opossum shrimp *Mysis* has an absorption spectrum peak at 515 nm and is found only in deep, clear, optically blue environments (Wetzel 1975). Other species such as the freshwater prawn *Macrobrachium rosenbergii* have a strong behavioural preference for dark coloured backgrounds, likely because they perceive dark colours as a refuge (Juarez *et al.* 1987). Thus, changes in the spectral quality of water could have profound effects on the behaviour of some invertebrates.

As noted earlier, increased water colour may inhibit the growth of periphytic algae. Invertebrate grazers may therefore be indirectly affected by the presence of water colour, through a decline in their food resources (Kullberg 1992). Kullberg (1992) observed that several taxonomic groups of benthic macro-invertebrates including the shredding trichopteran exhibited a negative correlation to water colour in 20

streams in southern Sweden. This study also noted that species richness declined as water colour increased when the pH was greater than 5.7.

4.1.4 Fish

As with invertebrates, many fish species have visual pigments that correspond to the spectral nature of their habitat. For example, freshwater species typical of photically blue environments (e.g., clear, deep lakes) have more pigments in the blue and green portions of the visible spectrum (Wetzel 1975). Thus, changes in water colour could also affect the behaviour of fish.

Most studies of the effects of water colour to fish have focussed on the interaction between colour and toxicity of metals. For example, several studies have shown that aluminum, zinc and copper complex with humic substances in coloured water (Nilssen 1982; Winner 1985; Wilson 1972), thus reducing toxicity (Winner 1985; Hutchinson and Sprague 1987). Hutchinson and Sprague (1987) observed that the combined LC₅₀ for a mixture of Al/Zn/Cu to flagfish declined by a factor of 2.1 when apparent colour (i.e., water samples were not filtered) increased from 3 to 10 mg/L Pt.

Conversely, mercury availability, bioaccumulation and hence toxicity increase as water colour increases (Nilsson and Håkanson 1992; Haines *et al.* 1995; Mierle and Ingram 1991). Part of the reason for this relationship is that the mercury brought to an aquatic system from the surrounding catchment area is attached to coloured substances (Nilsson and Håkanson 1992; Mierle and Ingram 1991). This is also likely true for other metals. The difference is that other metals often remain bound to organics once in an aquatic system. Further, in deep water systems, mercury methylation by bacteria under anoxic conditions will likely be enhanced with higher concentrations of humic matter (Nilsson and Håkanson 1992). For deep lakes in Sweden, regression analyses indicate that an increase in water colour from 10 to 50 mg/L Pt was associated with an increase in mercury tissue levels in fish of between 23.4 and 82.8%, depending on fish species, and location, and depth of lake (Nilsson and Håkanson 1992).

4.2 Literature Criteria

Based on a review of the literature, few jurisdictions have derived criteria for the protection of marine, freshwater aquatic life, either for apparent or true colour (Tables 1 and 2). The CCME (1987 and updates) does not have colour guidelines for the protection of freshwater or marine aquatic life.

Table 1. Colour criteria for freshwater aquatic life.

Criteria Statement	Criteria Values	Reference
The combined effect of colour and turbidity should not change the compensation point more than 10% from its seasonably established norm, nor should such a change place more than 10% of the biomass of photosynthetic organisms below the compensation point.		US EPA (1972)

Settleable and suspended solids should not reduce the depth of the compensation point for photosynthetic activity by more than 10% from the seasonally established norm for aquatic life.		US EPA (1976)
Not to be increased more than 30 colour units above natural value.	Less than or equal to 30 mg/L Pt above background	Alberta Environmental Protection (1994)
The increase in colour (in combination with turbidity) must not reduce the depth of the compensation point for photosynthesis by more than 10% of the established seasonal norm for aquatic life.		Ministère de l'environnement du Québec (1992)
Less than 10% change in euphotic zone where water column is greater than 0.5x euphotic zone; for shallower waters, maximum reduction in light at the sediment bed should not exceed 20%.		Australia (1992)

Table 2. Colour criteria for marine aquatic life.

Criteria Statement	Criteria Values	Reference
Shall not reduce the depth of the compensation point for photosynthetic activity by more than 10%. In addition, shall not reduce the maximum Secchi disc depth by more than 10%.		Alaska Department of Environmental Conservation (1979)
Less than 10% change in euphotic zone where depth is greater than 0.5x euphotic zone; for shallower waters, maximum reduction in light at the sediment bed should not exceed 20%.		Australia (1992)

With the exception of the colour criterion derived by the Province of Alberta (Alberta Environmental Protection 1994), the criteria for the protection of freshwater and marine aquatic life do not specify a particular true colour value or values, but rather are narrative statements about the effects that are to be avoided (US EPA 1972, 1976; Alaska Department of Environmental Conservation 1979; Ministère de l'environnement du Québec 1992; Australia 1992). No rationale was provided to support the colour criterion by the Province of Alberta.

4.3 Proposed Criteria

4.3.1 Apparent Colour

The 30-day mean transmission of white light shall be less than or equal to 80% of background levels as measured historically or at appropriate reference sites. This criterion applies to freshwater, estuarine and marine aquatic systems. The 30-day mean calculation should be based on a minimum of five weekly samples taken over a period of 30 days. Estimating percentage transmission of white light requires simultaneous measurements of light intensity at the surface and at a selected depth (generally below 1 m to avoid effects from surface agitation). Percent transmittance is based on total white light and is thus a composite for all visible wavelengths, each of which is variously influenced by water, dissolved matter and particulate matter (Wetzel 1975). Eloranta (1978) measured light penetration in water with a 'Submarine Fotometer' consisting of an underwater selenium photocell equipped with 2 mm thick Schott filters with peak transmissions at 432 nm (blue), 527 nm (green), and 627 nm (red) and connected with a micro-ammeter. Using such an apparatus, percent transmittance (per m) relative to surface incident light could be estimated by averaging across wavelengths. Precision may be increased by including more wavelengths.

4.3.2 True Colour

The 30-day mean true colour of filtered water samples shall not exceed background levels by more than 5 mg/L Pt or (> 5 true colour units) in clearwater systems (background levels less than or equal to 20 mg/L Pt) or 20% in coloured systems (background levels >20 mg/L Pt). This criterion applies to freshwater, estuarine and marine aquatic systems. The 30-day mean calculation should be based on a minimum of five weekly samples taken over a period of 30 days. *In situ* single wavelength analysis at 456 nm with the results calibrated against the Hazen measurement scale is the preferred analytical methodology for true colour. Section 1.4 and Bennet and Drikas (1993) describe this methodology in more detail.

4.4 Rationale

4.4.1 Apparent Colour

All the criteria available for apparent colour in general are related to changes in colour relative to background volume. The review of the literature on effects indicated that relatively small changes in light attenuation by dissolved organic matter and/or suspended particulates can have a profound impact on the lower limit of the euphotic zone (Eloranta 1978). This effect can lead to reductions in primary productivity (Parker and Sibert 1976; Haynes *et al.* 1994; Christensen *et al.* 1996), coverage of submersed macrophytes (Orth and Moore 1983; McPherson and Miller 1987; Gallegos and Kenworthy 1996), and indirect impacts at higher trophic levels in both freshwater and estuarine systems (Kullberg 1992). Therefore, an increase in apparent colour, as a result of anthropogenic inputs, should be of concern.

Percent transmission of light is an easily measured parameter that indicates the amount of photosynthetically active radiation available to primary producers at lower depths (Wetzel 1975). Transmission of white light is a function of both components of apparent colour, dissolved and particulate matter, and therefore is a useful monitoring tool for this parameter (Jerome *et al.* 1994a,b). Transmission of white light will exhibit considerable spatial, year-to-year, and seasonal variation in British Columbia

aquatic systems (Jerome *et al.* 1994a). Thus, it is not useful to specify a single value as the ambient water quality criterion for apparent colour. A more useful approach is to determine whether a particular anthropogenic activity (*e.g.*, road construction, harvesting of forests) is causing a decrease in transmission of white light compared to historical conditions or to background conditions in nearby aquatic systems. We have arbitrarily selected a 20% reduction in the amount of white light transmission for the criterion to ensure minimal impacts on productivity.

The sampling design used to determine whether transmission of white light has been reduced by less than 20% as a result of an anthropogenic activity needs to be flexible. Some considerations include availability of historical data and/or reference sites, nature of the anthropogenic activity (*e.g.*, point versus diffuse sources), and various legal and economic issues. Short-term changes in apparent colour (*e.g.*, <24 hours) can arise due to natural events (*e.g.*, storms) and are unlikely to have serious impacts on primary producers. Therefore, when testing whether a particular anthropogenic activity has caused an increase in apparent colour above the water quality criterion, several samples (*n* greater than or equal to 5) should be taken over a 30-day period and a mean calculated (or median if the data are right skewed).

4.4.2 True Colour

Changes in the spectral quality of light in water can have a profound impact on primary productivity (Gallegos and Kenworthy 1996), phytoplankton species composition (Atlas and Bannister 1980; Ilmavirta and Huttunen 1989), and foraging behaviour and habitat selection of invertebrates and fish (Kullberg 1992; Juarez *et al.* 1987; Wetzel 1975). Several studies have shown that increases in true colour of approximately 5 mg_L⁻¹ Pt in clearwater systems can have a profound impact on the depth of the euphotic zone (Eloranta 1978) and photosynthetic rates of algae and macrophytes (Gallegos and Kenworthy 1996). This is the basis for true colour criterion in clearwater systems. Further increases in colour have a less dramatic impact on depth of the euphotic zone (Eloranta 1978). The 20% above background cutoff for coloured systems is somewhat arbitrary. The value could not have been much lower because natural variation would lead to frequent criterion exceedances.

Changes in spectral quality are much more influenced by changes in true colour than by changes in concentrations of particulate matter, because the latter have relatively non-selective scattering properties. The appropriate wavelength range for determining spectral quality and hence true colour should be in the blue portion of the spectrum because water absorption is low in this region and because humic and fulvic acids exhibit equal absorbance to the standard Pt-Co reference solution around 410 nm and 445-470 nm (Bennett and Drikas 1993; Hongve and Akesson 1996). Therefore, the Pt-Co colour standard is an adequate measure for true colour in aquatic systems. Note that colourimetric measures of true colour are more precise than are comparator methods, although both can be used to determine true colour.

As with apparent colour, the sampling design used to determine whether the true colour criterion has been exceeded as a result of an anthropogenic activity needs to be flexible. Some considerations include availability of historical data and/or reference sites, nature of the anthropogenic activity (*e.g.*, point versus diffuse sources), and various legal and economic issues. Short-term changes in true colour (*e.g.*, <24 hours) can arise due to natural events (*e.g.*, storms) and are unlikely to have serious impacts on primary producers. Therefore, when testing whether a particular anthropogenic activity has caused an

increase in true colour above the water quality criterion, five weekly samples should be taken over a 30-day period and a mean calculated (or median if the data are right skewed).

5. Wildlife

5.1 Effects

Several studies have found that species abundance and/or reproductive success of wildlife may be positively or negatively correlated with water colour. For example, negative relationships between breeding success of common loons and Pacific loons in Ontario, Quebec, Minnesota and Alaska and water colour have been demonstrated (Alvo *et al.* 1988; Heglund *et al.* 1994). Loons are sight feeders that generally feed on the nest lake. Thus, it is advantageous for loons to nest near relatively clearwater systems. Heglund *et al.* (1994) found that on average, Pacific loons occurred on lakes and ponds with colour values about two-thirds the values of lakes and ponds without loons (loons present ~50 - 75 mg/L Pt, loons absent ~80 - 120 mg/L Pt). Other species, however, have distributions that are positively correlated with water colour. The distribution of Blanding's Turtles (*Emydoidea blandingii*), Painted Turtles (*Chrysemys picta*), and Great Blue Herons (*Ardea herodias*) closely parallels the distribution of highly coloured acidic waters and peaty soils in Nova Scotia (Power *et al.* 1994). In all but one instance, Blanding's turtles were only found in lakes and streams with true colour >60 mg/L Pt. The association between turtle and heron abundance and water colour is likely related to the higher secondary productivity typical of highly coloured systems.

5.2 Literature Criteria

No water quality criteria for the protection of wildlife were found in the literature for either true or apparent colour.

5.3 Proposed Criteria

5.3.1 Apparent Colour

The 30-day mean transmission of white light shall be greater than or equal to 80% of background levels as measured historically or at appropriate reference sites. This criterion applies to freshwater, estuarine and marine aquatic systems. The 30-day mean calculation should be based on a minimum of five weekly samples taken over a period of 30 days. The appropriate methodology for determining transmission of white light is noted in section 4.3.1.

5.3.2 True Colour

The 30-day mean true colour of filtered water samples shall not exceed background levels by more than 5 mg/L Pt in clearwater systems (background levels less than or equal to 20 mg/L Pt) or 20% in coloured systems (background levels >20 mg/L Pt). This criterion applies to freshwater, estuarine and marine

aquatic systems. The 30-day mean calculation should be based on a minimum of five weekly samples taken over a period of 30 days. The appropriate methodology for determining transmission of white light is noted in section 4.3.2.

5.4 Rationale

The limited wildlife effects information indicates that changes in water colour could lead to some species avoiding particular habitats. The available information is, however, insufficient to define numerical criteria for the protection of wildlife that would be different from the aquatic life criteria. The aquatic life criteria should be protective of wildlife because the changes in colour associated with declines in loon abundance and reproductive success (~50% increase in colour) are greater than those specified in the criteria. For monitoring programs, it is also cost efficient to use the same analytical protocols for different water uses.

6. Livestock

6.1 Effects

To our knowledge, no known effects of colour to livestock have been documented.

6.2 Literature Criteria

There are no criteria specific to livestock watering available from any other jurisdiction. Alberta has set general criteria intended to protect most water uses (Alberta Environmental Protection 1994). It is not known, however, whether livestock watering will be protected by the Alberta criterion of no increases greater than 30 mg/L Pt above background.

6.3 Proposed Criteria

There is insufficient information to derive water quality criteria for apparent and true colour for this water use.

6.4 Rationale

The limited information on the toxicity of humic and fulvic acids to mammals (see Section 3.2) indicates that livestock are not likely to be adversely affected by coloured waters. If the water was to impart a toxic effect to livestock, it would be due to other physical, biological and/or chemical parameters in the water. Existing criteria for these parameters should protect livestock from being harmed.

7. Irrigation

7.1 Effects

To our knowledge, no known effects of colour to irrigation have been documented.

7.2 Literature Criteria

There are no criteria specific to irrigation available from any other jurisdiction. Alberta has set general criteria intended to protect most water uses (Alberta Environmental Protection 1994). It is not known, however, whether the protection of irrigated crops will be accomplished by the criterion of no increases greater than 30 mg/L Pt above background.

7.3 Proposed Criteria

There is insufficient information to derive water quality criteria for apparent and true colour for this water use.

7.4 Rationale

The effects to plants of coloured water observed in aquatic systems are due to reductions in light quality and quantity. Such effects are highly unlikely for terrestrial plants exposed to coloured irrigation waters. If the water was to impart a toxic effect to crops, it would be due to other physical, biological and/or chemical parameters in the water. Existing criteria for these parameters should protect crops from being harmed.

8. Recreation and Aesthetics

8.1 Effects

Visual clarity is an important attribute of natural waters because it has a strong influence on their perceived recreational value, particularly for swimming and diving. Several studies have found that a minimum water quality of 1.1 to 1.2 m black disk sighting range (=1.4 to 1.5 m Secchi disk depth) was required before the water was considered to be suitable for bathing by 75% of the public (Smith and Davies-Colley 1992; Smith et al. 1991). These studies also showed that yellow-hued waters are poorly regarded, whilst green-yellow waters are considered marginal, and green to blue colours are preferred (Smith and Davies-Colley 1992). Green to blue waters generally have a true colour of less than or equal to 15 mg/L Pt (Wetzel 1975; McPherson and Miller 1987). Public perception of water quality based on clarity and colour are very similar for both aesthetic and bathing uses (Smith and Davies-Colley 1992).

8.2 Literature Criteria

Most criteria for the protection of recreation and aesthetics water uses for true and apparent colour are narrative statements. For example, a compilation of state and federal criteria by the US EPA indicated that ten states were using terms like "substantial visible contrast", or "substantial change in turbidity" (US

EPA 1980; US EPA 1988). In Europe, for colour of bathing waters there is the standard "no abnormal change" (EEC 1976).

To protect the aesthetic quality of a water body, Australia and New Zealand specify that the natural visual clarity of water should not be reduced by more than 20%, and the natural hue of the water should not be changed by more than 10 points on the Munsell scale (Australia 1992; New Zealand 1994). The Alberta water quality guideline for most water uses is that colour should not be increased more than 30 mg/L Pt above natural value (Alberta Environmental Protection 1994). The Canadian water quality guideline for recreation and aesthetics states that a secchi disc be visible at a minimum water depth of 1.2 m (CCME 1987). No rationale is provided for the guideline beyond a general concern that "swimming areas are clear enough for users to estimate depth and to see subsurface hazards easily". The Japanese water quality guideline for aesthetic uses is 40 mg/L Pt, while the guideline for water use involving public contact is 10 mg/L Pt (Takahashi 1991).

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8.3 Proposed Criteria

8.3.1 Apparent Colour

The 30-day mean Secchi disk sighting range should be greater than or equal to 1.5 m. This criterion applies to freshwater, estuarine and marine aquatic systems. The 30-day mean calculation should be based on a minimum of five weekly samples taken over a period of 30 days.

8.3.2 True Colour

The 30-day mean true colour of water should be less than or equal to 15 mg/L Pt (i.e., blue to green water). This criterion applies to freshwater, estuarine and marine aquatic systems. The 30-day mean calculation should be based on a minimum of five weekly samples taken over a period of 30 days.

8.4 Rationale

The apparent colour criterion is based on the studies conducted in New Zealand on public perception of what constitutes acceptable water quality for recreational uses (Smith and Davies-Colley 1992; Smith et al. 1991). No other studies were available concerning the effects of colour to this water use. More stringent site-specific ambient criteria (i.e., Secchi disk sighting range greater than or equal to 4 m) will be required for recreational waters used for diving. Stricter criteria will ensure that potentially dangerous submerged objects are visible to divers.

Several studies have shown that yellow waters are poorly regarded and blue to green waters preferred by recreational water users (Smith and Davies-Colley 1992; Smith et al. 1991). In general, waters with a true colour of less than or equal to 15 mg/L Pt should be in the blue to green colour range (Wetzel 1975).

Systems that are naturally coloured are not normally used for recreational purposes, and thus this criterion is not based on a change in background levels. The method for determining true colour is the same as that described in section 4.3.2.

The sampling design used to determine whether the colour criteria have been exceeded as a result of an anthropogenic activity needs to be flexible. Some considerations include availability of historical data and/or reference sites, nature of the anthropogenic activity (e.g., point versus diffuse sources), and various legal and economic issues. Short-term changes in true and apparent colour (e.g., <24 hours) can arise due to natural events (e.g., storms) but are unlikely to have serious impacts on primary producers. Therefore, when testing whether a particular anthropogenic activity has caused an increase in colour above the water quality criteria, five weekly samples should be taken over a 30-day period and a mean calculated (or median if the data are right skewed).

9. Industrial Water Supplies

9.1 Effects

Colour-causing constituents may cause foaming in boilers, hinder precipitation methods (e.g., iron removal or water softening) or impart a colour to finished products.

9.2 Literature Criteria

In Australia, all waters for the textile, tanning and leather industries must have a true colour of less than 5.0 mg/L Pt (Australia 1992). For the food and beverage industry, the guidelines are <5.0 mg/L Pt for water used in brewing, canning, freezing and processing, and <10 mg/L Pt for water used in baking and carbonated drinks.

9.3 Proposed Criteria

No water quality criteria are proposed for apparent and true colour for this water use.

9.4 Rationale

Colour criteria for industrial water use are not likely necessary because industries requiring very clear water (e.g., production of fine paper) generally treat the water to remove true and apparent colour prior to use.

10. Research and Development Needs

There are several measurement scales for true and apparent colour that provide much more information than measurements using the Hazen scale or transmission of white light (e.g., tristimulus system, Munsell system). There are, however, few or no monitoring or effects data available using these measurement scales, and thus it was not possible to derive aquatic life or wildlife criteria using the

preferred measurement scales. Research on how changes in colour measured in chromaticity or Munsell units affect biota would be very useful for future criteria development.

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