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Colours of Natural Waters: 2. Observations of Spectral Variations in British Columbia Rivers

Abstract

Subsurface volume reflectance spectra in the range 400-740 nm were directly measured on four separate occasions at each of fourteen river stations in British Columbia during 1986 and 1987. Chromaticity analyses were performed on volume reflectance spectra to define aquatic colour in terms of a dominant wavelength and its associated purity. An attempt was made to explain water colour variations in British Columbia river systems based upon elevation. drainage area, glacial-feed, groundwater intrusion, turbidity, and basin type. It is shown that simple sub-basins which are glacier-fed and meltwater-dominated generally display dominant wavelengths in the interval 480-550 nm (i.e. colours usually perceived to be in the range blue to turquoise to green), a consequence of low to moderate turbidity comprised predominantly of suspended inorganics. Simple sub-basins which are non glacier-fed and groundwater-dominated display dominant wavelengths in the interval 550-570 nm (i.e. colours perceived to be in the range green to brown). a consequence of low to high particulate turbidity in conjunction with substantial concentrations of dissolved organics. Most of the large river basins of the Canadian Cordillera are comprised of a complex of sub-basins, and thus represent the integration of inputs from several sources. These complexes are shown to display dominant wavelengths in the restricted wavelength interval 573-578 nm. Such an "end-point" dominant wavelength causes the river water to be perceived as brownish in colour.

Introduction

In our companion paper (Jerome *et al.* 1994) we have described how the observed colour of a natural water body (in terms of the dominant wavelength of its upwelling irradiance spectrum) is a direct consequence of the absorption and scattering properties (as a function of wavelength) that may be confidently ascribed to a unit concentration of each of the principal organic and inorganic components of that water body.

Natural water masses, particularly those strongly influenced by the proximity of land masses, display both spatial and temporal variations in their organic and inorganic compositions. Consequently, they will be characterized by related variabilities in their associated dominant wavelengths. Such colour variability is exhibited throughout the British Columbia river systems. This is a result of the geological and vegetative diversity characterizing the Canadian Cordillera and the impact of such diversity on the composition of associated natural water bodies.

This paper presents the results of an optical survey of British Columbia river stations taken during 1986 and 1987. An attempt to quantify the visual colour of natural water in terms of the human eye's spectral response is discussed, as are possible explanations for the visual colour variations defining the British Columbia river systems.

Sampling Stations

Figure 1 illustrates the location of the fourteen sampling stations used in the current survey. All stations are river-based and all form part of a network of sampling stations in southern British Columbia operated under the auspices of the Inland Waters Directorate of Environment Canada. Also shown in Figure 1 are the drainage basins for the surveyed rivers.

Subsurface volume reflectance (the ratio of upwelling irradiance to downwelling irradiance at a specified depth) spectra were determined at each station throughout the spectral range 400-740 nm utilizing a Techtum QSM 2500 scanning Quantaspectrometer. Each station was visited twice a year during 1986 and 1987, once in early summer and once in autumn, the intention being to sample at or near both peak and minimum flow rates. Table 1 lists the rivers, station locations (station numbers as shown in Figure 1), sampling dates, station elevations, and river flow rates for the station or a nearby station.

In addition to the subsurface optical spectra obtained at each station, water samples were collected to obtain concentrations of turbidity.

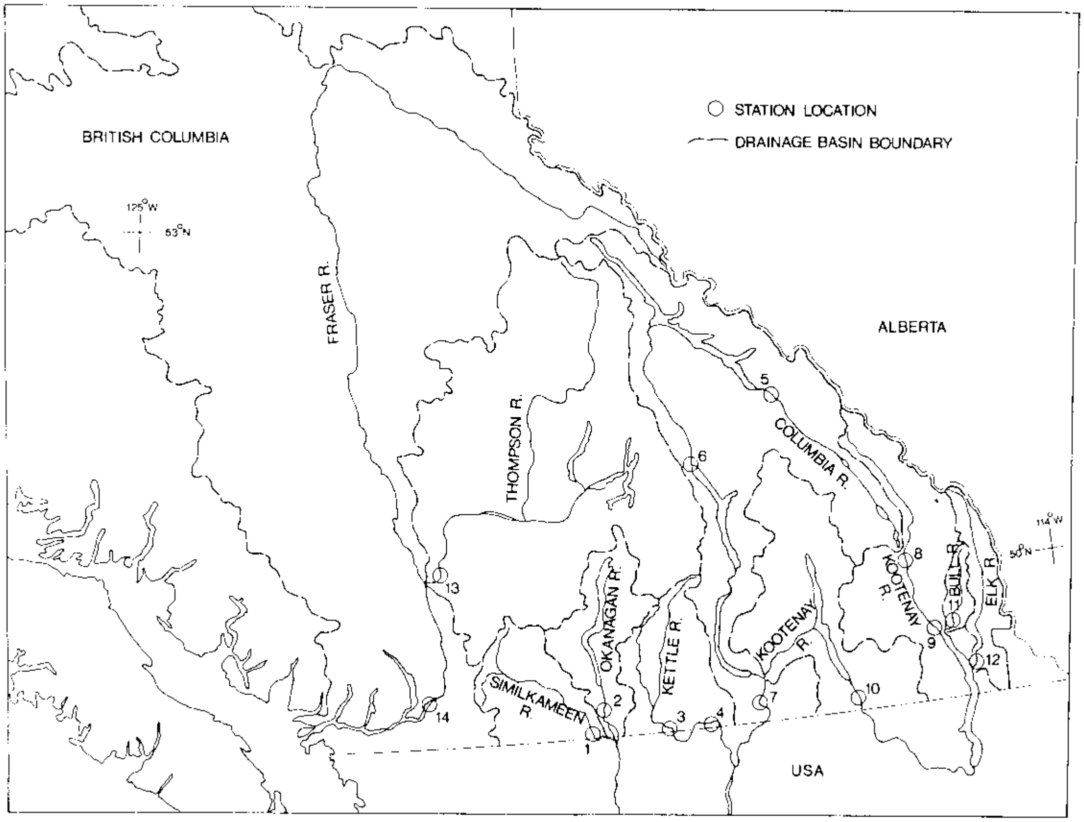

Figure 1. British Columbia river sampling stations.

In this study the optical measurements were performed *in situ* to eliminate the effects of surface reflection and to directly measure the subsurface volume reflectance of the water R(λ). These R(λ) spectra were then combined with an incident radiation spectrum for a standard atmosphere taken from Kneizys *et al.* (1988), to obtain an upwelling irradiance spectrum E(λ) for each station and each sampling date.

Volume Reflectance Spectra of British Columbia River Waters

Subsurface volume reflectances were measured twice a year during 1986 and 1987 for the fourteen river stations listed in Table 1. Large variations in both magnitude and spectral shapes were observed. These variations are illustrated in Figure 2 which displays the summer and fall subsurface volume reflectance spectra recorded at stations 3 (Kettle River at Midway), 6 (Columbia River at Revelstoke), 8 (Kootenay River at Canal Flats), and 14 (Fraser River at Hope). Measured values of subsurface volume reflectance of British Columbia river water ranged from as low as ~3% to as high as 15-20%

The subsurface volume reflectance spectra reported here were obtained at different local times during different Julian days. Consequently, incident radiation distributions resulting from various combinations of solar and sky irradiances were encountered. The volume reflectance spectra have not been normalized to, say, vertical sun angles and standard sky irradiance. Such normalization would certainly impact the magnitude of R(λ) (up to a maximum of ±25% of the measured value) but would not impact the spectral shape of R(λ). Normalization is, therefore, unessential to chromaticity analyses of subsurface volume reflectance.

Dominant Wavelengths of British Columbia River Waters

Using measured volume reflectance spectra and an incident radiation spectrum for a standard clean, dry atmosphere taken from Kneizys *et al.* (1988),

TABLE 1. British Columbia River sampling locations and dates.

Station Number	River and Location	Drainage Area km^2	Mean Annual Discharge (m^3/s)	Station Elevation (m)	Sampling Dates	Flow Rate (m^3/s)
1	Similkameen River	9180	65.2	365	15 June 1986	199
					29 Sept 1986	17
					22 June 1987	80
					20 Oct 1987	7
2	Okanagan River at Oliver	7590	17.6	305	15 June 1986	37
					29 Sept 1986	14
					22 June 1987	7
					20 Oct 1987	11
3	Kettle River at Midway	5750	43	550	15 June 1986	97
					30 Sept 1986	14
					23 June 1987	28
					20 Oct 1987	3
4	Kettle River at Gilpin	9840	82	520	15 June 1986	178
					30 Sept 1986	22
					23 June 1987	61
					20 Oct 1987	5
5	Columbia River at Donald	9710	174	785	2 Oct 1986	91
					25 June 1987	437
					22 Oct 1987	50
6	Columbia River at Revelstoke	26700	854	425	2 Oct 1986	1390
					25 June 1987	
					22 Oct 1987	
7	Columbia River at Trail	155000	2830	415	15 June 1986	2080
					23 June 1987	1840
					20 Oct 1987	1510
8	Kootenay River at Canal Flats	5390	87.2	810	1 Oct 1986	56
					24 June 1987	150
					21 Oct 1987	28
9	Kootenay River at Fenwick Station	13600	205	755	16 June 1986	642
					1 Oct 1986	91
					24 June 1987	305
					21 Oct 1987	49
10	Kootenay River at Creston	35500	449	545	16 June 1986	411
					30 Sept 1986	232
					23 June 1987	197
					21 Oct 1987	597
11	Bull River at Hatchery	1530	32.9	755	16 June 1986	70
					1 Oct 1986	18
					24 June 1987	36
					21 Oct 1987	7
12	Elk River at Highway #93	4450	75.7	700	16 June 1986	132
					1 Oct 1986	26
					24 June 1987	59
					21 Oct 1987	14
13	Thompson River at Spences Bridge	54900	775	225	3 Oct 1986	388
					25 June 1987	1740
					23 Oct 1987	211
14	Fraser River at Hope	217000	2720	45	16 June 1986	10300
					29 Sept 1986	1410
					22 June 1987	5760
					19 Oct 1987	912

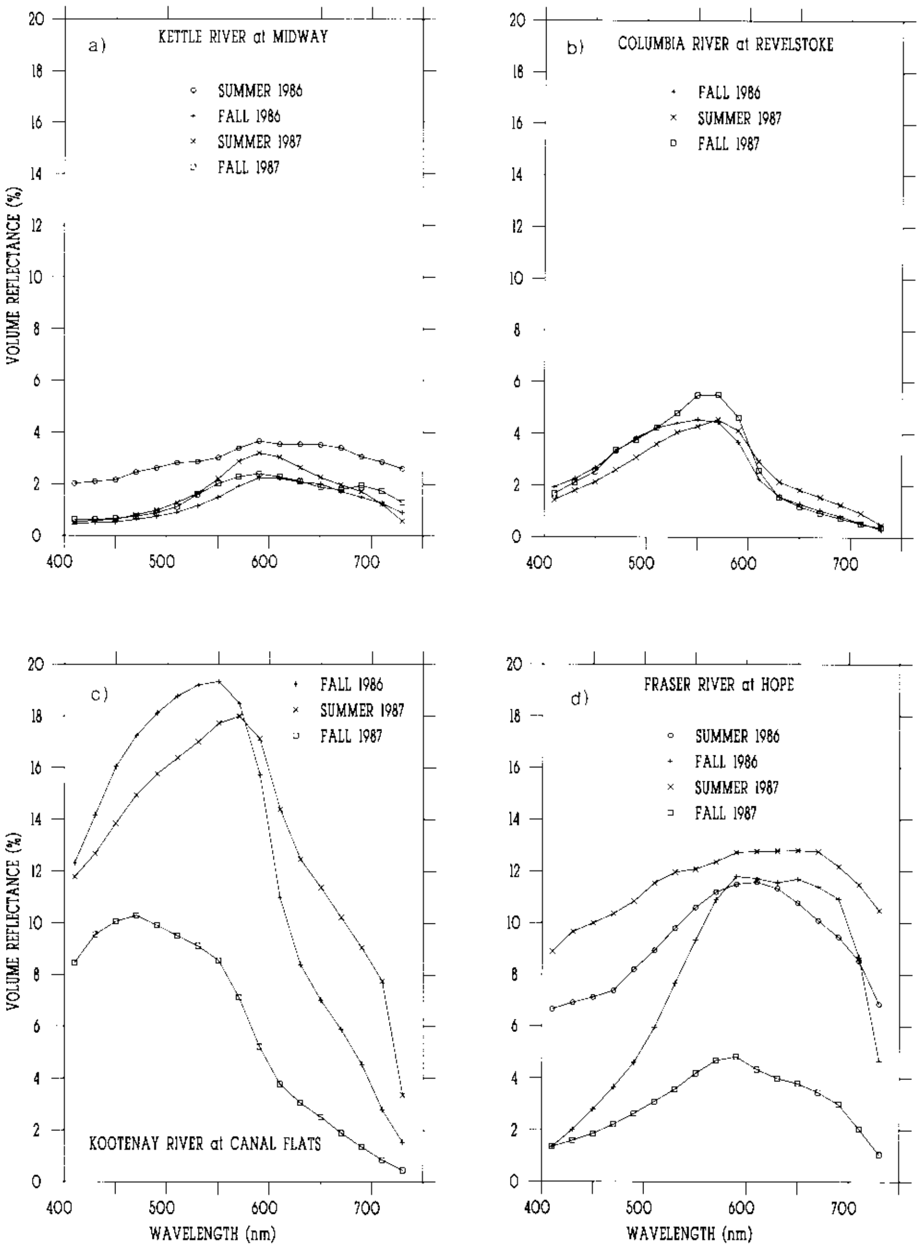

Figure 2. (a) Subsurface volume reflectance spectra recorded at Station 3 (Kettle River at Midway). (b) Subsurface volume reflectance spectra recorded at Station 6 (Columbia River at Revelstoke). (c) Subsurface volume reflectance spectra recorded at Station 8 (Kootenay River at Canal Flats). (d) Subsurface volume reflectance spectra recorded at Station 14 (Fraser River at Hope).

upwelling irradiance spectra were obtained for each station and sampling date. Chromaticity coordinates for each upwelling spectra were then calculated in the manner described in our companion paper (Jerome *et al.* 1994). Figures 3 and 4 illustrate chromaticity plots for stations 4 (Kettle River at Gilpin) and 14 (Fraser River and Hope), respectively. Also shown on Figures 3 and 4 are the white point S and the curve envelope. From the chromaticity plots the dominant wavelengths along with

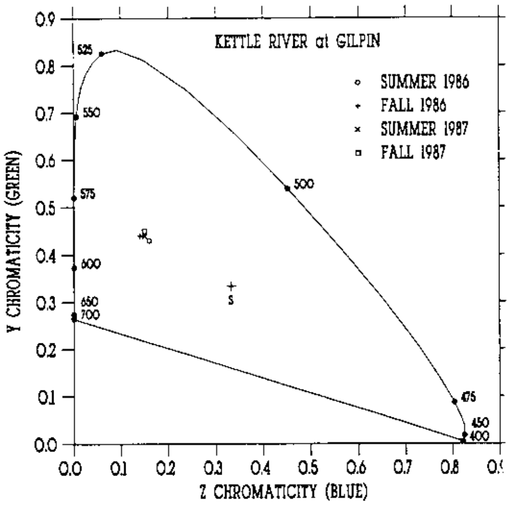

Figure 3. Chromaticity coordinate values for Station 4 (Kettle River at Gilpin).

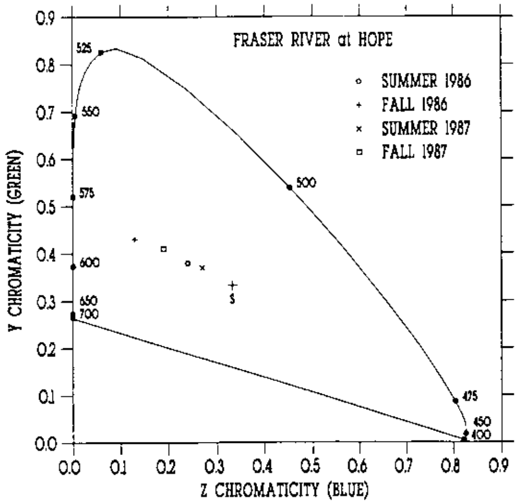

Figure 4. Chromaticity coordinate values for Station 14 (Fraser River at Hope).

their purity were determined for each upwelling spectrum for each station and each visit. An analysis of all fourteen stations showed that:

1) The points for a station may be closely clustered, e.g. Kettle River at Gilpin (station 4) and Columbia River at Trail (station 7). These stations display comparable dominant wavelengths and comparable purities.
2) The points for a station may be positioned along a line extending from the white point to the enveloping curve, e.g. Kettle River at Midway (station 3) and Fraser River at Hope (station 14). These stations display comparable dominant wavelengths but non-comparable purities.
3) The points for a station may be non-clustered, e.g. Kootenay River at Canal Flats (station 8) and Bull River at the Hatchery (station 11). These stations display non-comparable dominant wavelengths and non-comparable purities.

All the calculated dominant wavelengths and purity values are listed in Table 2. Two sets of entries are given for each station, namely the dominant wavelengths and purities observed in the summer and the dominant wavelengths and purities observed in the fall. The upper line records the 1986 values while the lower line records the 1987 results at each station.

Also included within Table 2 are turbidity values for each river station. Turbidity values were not obtained with the October 1986 optical data set. However, data from the regular Water Quality Branch Survey are listed in Table 2 when the Survey samples were obtained within a 24 hour period of the October 1986 spectro-optical measurements.

Dominant Wavelengths and River Basin Types

Glacier dynamics has accounted for much of the temporal evolution of the British Columbia landforms which display ubiquitous consequences of glacial ice erosion and deposition. Of the fourteen stations studied in the current work, eight are more responsive to glacial melt intrusions (the 3 Columbia River stations, the 3 Kootenay River stations, and the Bull and Elk River stations) than are the others. That is, stations 5, 6, 7, 8, 9, 10, 11 and 12 may contain significant consequences of a temporally varying glacial melt component, while stations 1, 2, 3 and 4 display minimal consequences of glacial melt intrusions. Stations 13 and 14 are far removed from the direct impact of glacial melt but glacial activity takes place within the drainage basin of these two rivers. In the ensuing discussions we will refer to stations 5-12 as glacier-fed and the remaining stations as non glacier-fed despite the realization that such a distinction is somewhat arbitrary.

The river water compositions are considered to be represented by the process hydrographs given

TABLE 2. Dominant wavelength, spectral purity, and measured turbidity for British Columbia river stations.

Station Number	River and Location	Dominant Wavelength Summer (nm)	Purity (%)	Summer Turbidity (JTU)	Dominant Wavelength Fall (nm)	Purity (%)	Fall Turbidity (JTU)
1	Similkameen River at U.S. Boundary	575	46	3.4	567	47	–
		569	43	0.8	549*	22	0.1
2	Okanagan River at Oliver	563	28	1.0	573*	46	0.2
		575*	46	0.5	578*	59	0.4
3	Kettle River at Midway	578	26	1.5	582	59	2.6
		580	63	0.3	578	57	0.1
4	Kettle River at Gilpin	576	53	1.4	575	57	0.5
		573	53	0.5	571	55	0.3
5	Columbia River at Donald	–	–	–	571	36	–
		575	37	1.5	569	22	0.3
6	Columbia River at Revelstoke	–	–	–	540	17	–
		562	31	8.9	553	26	1.0
7	Columbia River at Trail	567	16	1.5	–	–	–
		574	17	0.5	570	20	0.3
8	Kootenay River at Canal Flats	–	–	–	512	8	–
		558	13	13.0	489	20	0.2
9	Kootenay River at Fenwick Station	581	46	77.0	570	31	–
		573	31	16.0	551	15	0.3
10	Kootenay River at Creston	571	46	1.2	556	42	2.4
		570	46	0.8	554	27	0.3
11	Bull River at Hatchery	562	20	4.7	555	21	–
		552	12	1.4	507	13	0.1
12	Elk River at Highway #93	572	21	125.0	574	37	
		572	29	0.5	548	10	0.1
13	Thompson River at Spences Bridge	–	–	–	572	47	1.9
		568	42	2.2	573	49	0.3
14	Fraser River at Hope	576	28	43.0	579	61	10.0
		574	17	32.0	575	44	1.6

* contains interference from bottom reflectance

in Figure 5. Herein are sketched the anticipated seasonal dependencies of a representative river station which is glacier-fed and one which is non glacier-fed. The relative roles of snowmelt, glacial melt, and groundwater are illustrated in Figure 5. The role of groundwater for stations responsive to both snowmelt and glacial melt is distinctly less significant than the role of groundwater for stations only minimally impacted by glacial feed. While snowmelt and glacial melt are undoubtedly defined by suspended particulates displaying physical and optical differences, the composition of both types of runoff is almost exclusively inorganic in nature. The composition of groundwater, however, has a high probability of containing a substantial dissolved organic component in addition to its inorganic component. Consequently, non glacier-fed stations have a stronger likelihood of displaying the optical effects of a dissolved organic component than do glacier-fed stations.

Hence, summer optical spectra may be considered to represent river water comprised predominantly of snowmelt at glacier-fed stations, and some combination of snowmelt and groundwater at non glacier-fed stations. That is, summer subsurface volume reflectance spectra represent an optical response to suspended inorganic material at glacier-fed stations and an optical response to an admixture of organic and inorganic materials at non glacier-fed stations.

The fall optical spectra measured at glacier-fed stations may be considered to represent river water comprised of glacial melt containing suspended inorganic material. At non glacier-fed stations the

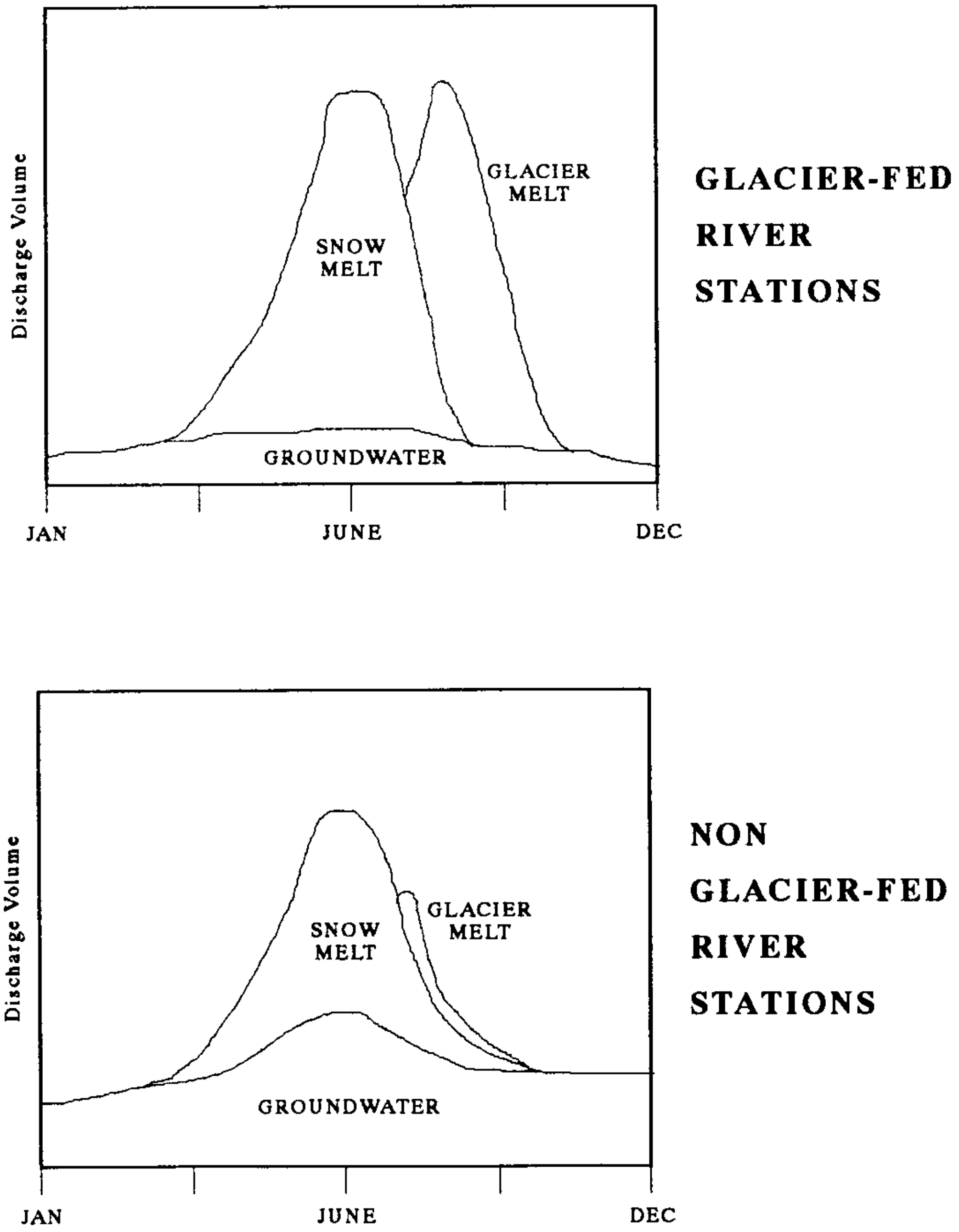

Figure 5. Idealized hydrographs illustrating the relative roles of snowmelt, glacial melt, and groundwater as components of the discharge volume for a) glacier-fed river stations and b) non glacier-fed river stations.

fall optical spectra may be considered to represent river water comprised predominantly of groundwater containing some combination of organic and inorganic material.

The river station hydrographs of Figure 5 represent the ideal situations of a simplified one-stream basin of uniform elevation. Most river basins do not display such a simplistic single source hydrographic profile. The dendritic patterns defining many river basins necessitate the integration of inputs from several possibly non-identical sources to obtain the realistic hydrograph for each river station. Figure 6 schematically illustrates a river basin that would require integration of a multitude of sources.

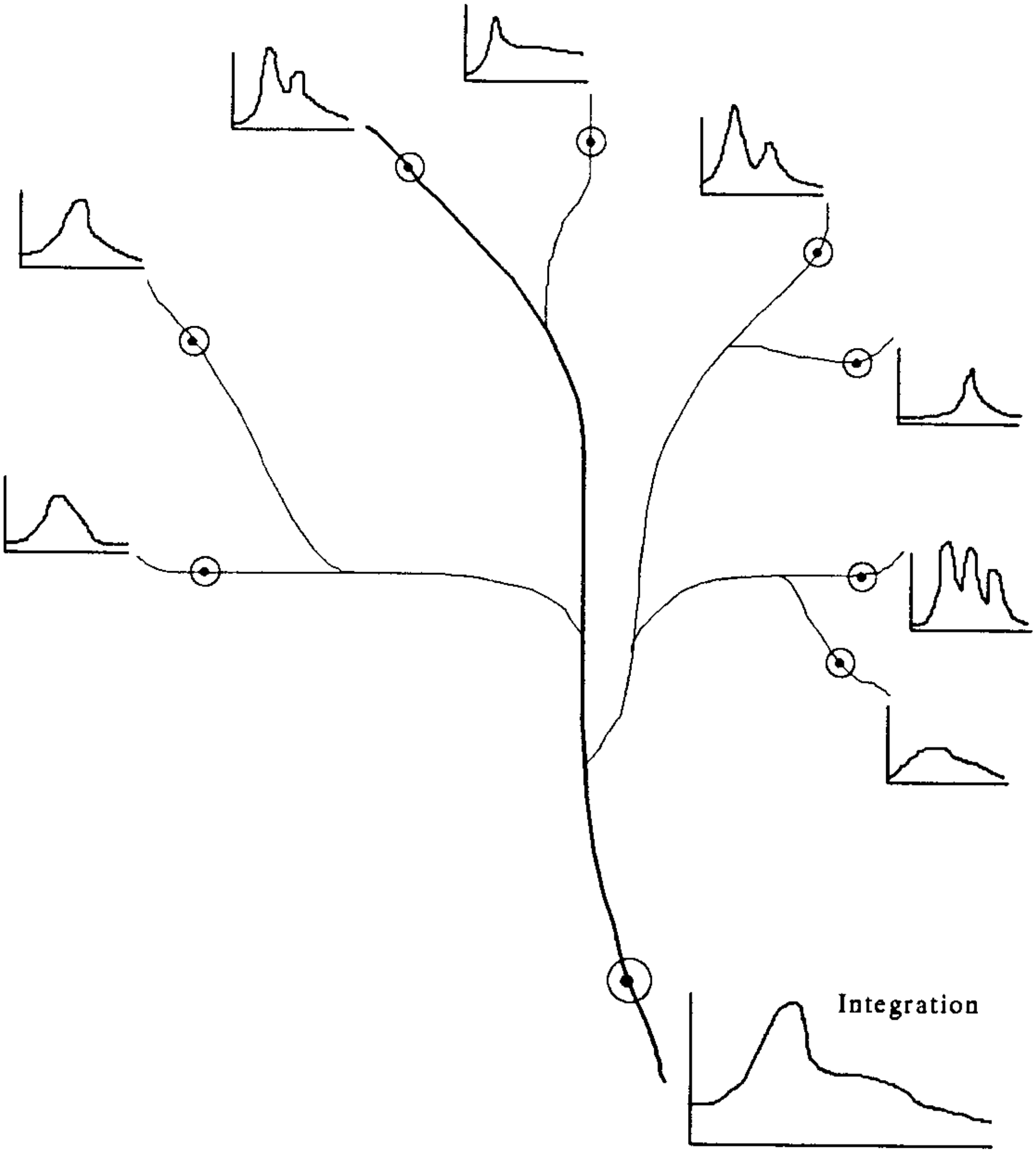

Figure 6. Schematic representation of a river station requiring the integration of hydrographs from multiple sources.

The Canadian Cordillera, like most large basin regions, therefore, can be considered as being comprised of a number of sub-units which can logically be divided into three basic types:

Type 1: Simple sub-basins which are predominantly glacier-fed.
Type 2. Simple sub-basins which are predominantly non glacier-fed.
Type 3. Complex basins which are integrations of a multitude of Type 1 and Type 2 sub-basins.

The salient features of the data contained in Table 2 may be summarized as follows:

1. Most of the dominant wavelengths lie in the spectral range 555 nm to 585 nm. Lower spectral ranges (489 nm to 548 nm) of dominant wavelengths were recorded during fall visitations to stations 1, 6, 8, 9, 10, 11 and 12. The low value of dominant wavelength observed at station 1 (Similkameen River) is a consequence of bottom reflection. The other stations, however, are glacier-fed and belong to the Type 1 basin classification. Only two glacier-fed stations (station 5 Columbia at Donald, and station 7 Columbia at Trail) displayed no dominant wavelengths in this lower spectral range for either fall visitation. These two stations, however, qualify as belonging to the Type 3 complex basin classification due to the many tributaries of the Columbia River.
2. Quite substantial variations (13 nm-52 nm) were observed between the two fall determinations at all but one of the river stations influenced by glacial melt. Once again the Columbia River at Donald (belonging to the Type 3 basin classification) behaved differently from its glacier-fed counterparts, displaying a fall-to-fall variation of only 6 nm. Unfortunately, logistical difficulties prevented obtaining a reliable optical spectrum at station 7 in the fall of 1986.
3. In addition to the fall-to-fall variabilities observed in the dominant wavelengths for nearly all the glacier-fed river stations, these glacier-fed stations also generally displayed significant summer-to-fall wavelength variabilities (9 nm-69 nm). Again, as explained earlier, exceptions to this behaviour pattern are the Columbia River stations at Donald and Trail.
4. Little variation (≤ 10 nm) was seen between the two summer determinations at all the river stations when bottom effects are neglected.
5. For each non glacier-fed river station the summer and fall dominant wavelengths were numerically similar, displaying differences <10 nm.
6. Wide ranges of turbidity were recorded throughout both sets of optical surveys. From Table 2 it is seen that low values of dominant wavelengths are always associated with low values of turbidity. High values of dominant wavelengths, however, can be associated with either high or low values of turbidity.

The features of the subsurface optical spectra observed in this study are not inconsistent with the theoretical results of our companion paper (Jerome *et al.* 1994) in which the dominant wavelengths of the upwelling irradiance spectra were related, through the optical cross sections of suspended minerals, chlorophyll, and dissolved organic carbon, to the co-existing concentrations of those aquatic components. Specifically:

1. Waters displaying low turbidity (i.e. low concentrations of suspended mineral and chlorophyll) along with low concentrations of dissolved organic carbon would be expected for glacier-fed, runoff-dominated river stations. These stations would display upwelling irradiance spectra characterized by low values of dominant wavelength.
2. Waters displaying low turbidity coupled with substantial concentrations of dissolved organic material would be expected for non glacier-fed groundwater-dominated river stations. These stations would display upwelling irradiance spectra characterized by intermediate to high values of dominant wavelength.
3. Waters displaying high turbidity could be expected for any station be it glacier-fed, non glacier-fed, or a complex integration of several Type 1 and/or Type 2 sub-basins. Such stations would display upwelling irradiance spectra characterized by high values of dominant wavelength.

Dominant Wavelengths and Basin Parameters

Since the dominant wavelength observed at a river station is a direct consequence of the organic and inorganic matter comprising the water column at the time of observation, the dominant wavelength can logically be expected to be dependent upon

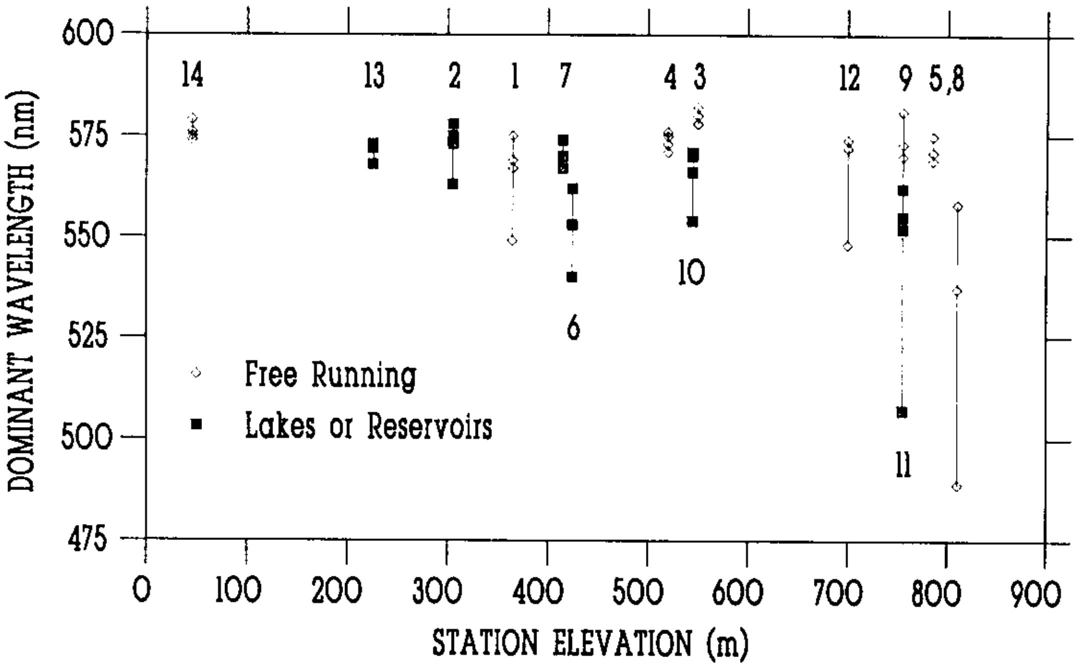

Figure 7. Range of dominant wavelengths observed at each river station plotted against the station elevation. Stations are numbered as in Table 1.

those basin parameters and/or activities that dictate aquatic composition. In addition to the nature and source of the water, such basin parameters as elevation, discharge flow rates, drainage area, and the presence and size of reservoirs and lakes can influence the quantities of the organic and inorganic components in river waters. Possible relationships among British Columbia river water colour and these basin parameters were explored.

Figure 7 displays the range of dominant wavelengths (summer and fall of each of two years) plotted against the station elevation in metres. Stations in rivers containing lakes or reservoirs are distinguished in Figure 7 from those stations in rivers that are free running. The presence of lakes or reservoirs can modulate river flow which may or may not result in a colour differential being observed between river water entering and vacating the lake or reservoir.

Figure 7 suggests a relationship between range of dominant wavelength and station elevation with stations at higher elevations displaying a wider range of dominant wavelengths. For the stations included within this study, the presence or absence of impoundments in the river does not appear to significantly impact this relationship. The stations showing the highest elevations, and therefore the largest wavelength range in Figure 7 are the glacier-fed stations. Further, as seen from Figure 7, the upper limit to the range of dominant wavelengths appears to be independent of the elevation of the station sampled. Consequently, it is the lower limit of the dominant wavelength range which is inversely related to station elevation. As discussed in our companion paper (Jerome *et al.*, 1994), low values of dominant wavelength are associated with aquatic regimes containing small concentrations of suspended inorganic material. This suggests that glacial meltwater is characterized by either low turbidity values (if the optical cross sections of suspended mineral in the B.C. rivers are comparable to those observed for suspended minerals in Lake Ontario) or possible intermediate turbidity values (if the suspended mineral in the glacial meltwater are characterized by a flat, i.e. "white" optical cross section spectrum). In either case, the direct observations of this experimental work appear to be in good agreement with the theoretical analyses of our companion work.

There is evidence to support the possibility that a "white" optical cross section spectrum may indeed define the suspended material in the glacial

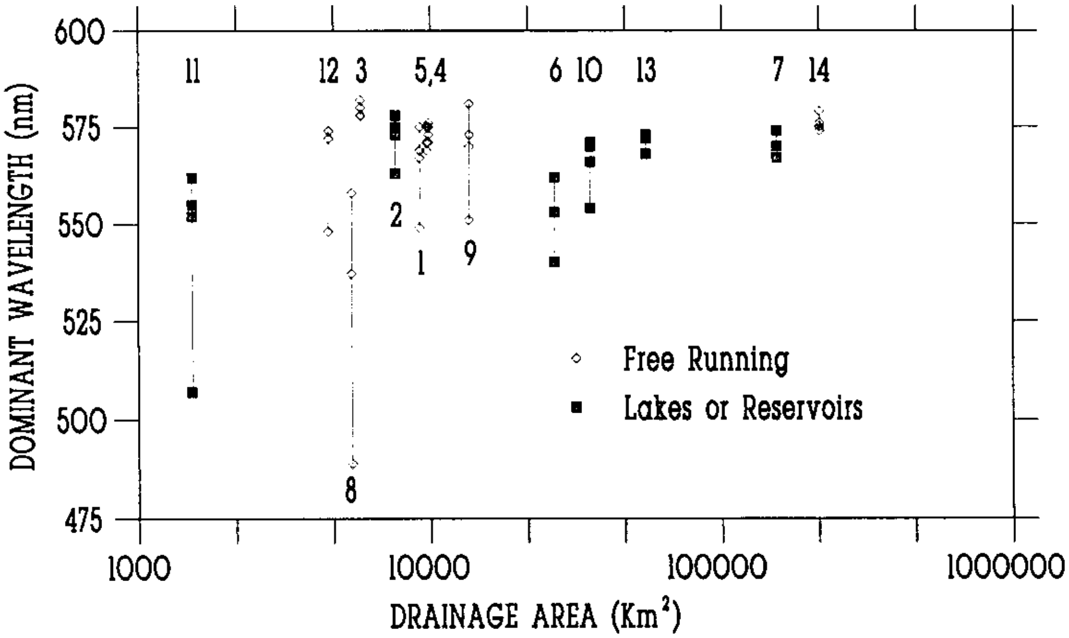

Figure 8. Range of dominant wavelengths observed at each river station plotted against the drainage area of the river upstream from the station. Stations are numbered as in Table 1.

feed. Low values of the chromaticity purity (as seen from Table 2) are generally observed for glacier-fed stations. Also, the very high values of volume reflectance observed in the glacier-fed stations Canal Flats and the Hatchery are strongly suggestive of the presence of "white" scattering centres. These B.C. river observations are consistent with the work of Aas and Bogen (1988) who observe that the "milky" runoff of some Norwegian glaciers is a consequence of larger diameter particles which tend to settle out downstream. Such settling could certainly be hastened by the presence of impoundments within the river, although free running rivers could also be characterized by such settling, depending upon stream flow velocity.

Figure 8 displays the range of dominant wavelengths plotted against the drainage area of the river upstream of the station location. A general relationship appears to emerge, with stations associated with large drainage areas displaying a relatively constant value of dominant wavelength, and stations associated with smaller drainage areas displaying larger ranges of dominant wavelength. This is undoubtedly a consequence of large drainage areas being associated with river stations belonging to the complex Type 3 classification. Such integrated source stations would tend to be characterized by waters displaying high degrees of homogeneity. Once again the presence or absence of impoundments appears to be of little or no significance.

No distinct relationship between range of dominant wavelength and mean annual flow emerged for the stations considered in this study.

Conclusions

For the Canadian Cordillera, Type 1 sub-basins may be defined as having the following properties: high elevation, small drainage areas, strong influence from runoff associated with both snowmelt and glacial melt, low to moderate turbidity values, relatively constant upper limit of dominant wavelength, and non constant lower limit of dominant wavelength. These Type 1 sub-basins generally display dominant wavelengths in the wavelength interval 480-550 nm., i.e. colours perceived to be in the range blue to turquoise to green, a consequence of predominantly suspended inorganic materials.

Type 2 sub-basins may be defined as having the following properties: lower elevations, large or small drainage areas, minimal influence from glacial meltwater, substantial influence from snowmelt and from groundwater intrusion, low to high turbidity values, and relatively constant upper and lower limits of dominant wavelength. These Type 2 sub-basins display dominant wavelengths in the wavelength interval 550-570 nm., i.e. colours perceived to be in the range green to brown, a consequence of substantial concentrations of dissolved organic materials.

Type 3 basins may be defined by any combination of the physical basin parameters (elevation, drainage area, source waters) defining the Types 1 and 2 sub-basins. Dominant wavelengths in the wavelength interval 573-578 nm were consistent features of the optical spectra observed at these stations. This suggests that the Cordilleran waters tend to approach an "end-point" aquatic colour defined by dominant wavelengths of these values. This is consistent with the "end-point" dominant wavelength values 572-583 nm illustrated in our companion paper (even though the optical cross sections appropriate to Lake Ontario were used in generating those results). Such "end-point" aquatic colour with the 573-578 nm dominant wavelength range could be attained in any of three possible ways: 1) high concentrations of suspended minerals, 2) high concentrations of chlorophyll, or 3) low concentrations of suspended minerals coupled with high concentrations of dissolved organic materials. River water at stations included within Type 3 basins consistently display brown colours.

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