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MODEL FOR SPECTRAL COLOUR VARIATIONS OF BRITISH COLUMBIA RIVER WATERS

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MODEL FOR SPECTRAL COLOUR VARIATIONS OF BRITISH COLUMBIA RIVER WATERS

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MANAGEMENT PERSPECTIVE

The optical model developed at NWRI for relating water colour to the organic and inorganic components co-existing within inland lakes has direct application to river systems. This is dramatically shown in this joint venture between NWRI and the Water Quality Branch in Vancouver. A two year study of water colour variations at fourteen river stations in the Canadian Cordillera has enabled the water quality model to successfully interpret the colour of British Columbia river water in terms of elevation, drainage area, glacial-feed, groundwater intrusion, and complexity of input sources.

PERSPECTIVE GESTION

Le modèle optique développé à l'INRE pour relier la couleur de l'eau aux composantes organiques et inorganiques coexistantes dans les lacs intérieurs a une application directe au niveau des réseaux des rivières. L'entreprise conjointe entre l'INRE et la Direction de la qualité des eaux à Vancouver illustre de façon spectaculaire cette relation. Dans le cadre d'une étude de deux ans portant sur les variations de la couleur de l'eau au niveau de quatorze stations hydrographique de la Cordillère canadienne, il a été possible, grâce au modèle sur la qualité de l'eau, d'interpréter avec succès la couleur de l'eau des rivières de la Colombie-Britannique en fonction de l'altitude, de la superficie du bassin, de l'alimentation par l'eau de fonte des glaciers, de l'intrusion des eaux souterraines et de la complexité des sources d'alimentation.

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 such continuous volume reflectance spectra to define aquatic colour in terms of a dominant wavelength and its associated purity. Using the concept of "optical cross sections" (a quantification of the scattering and absorption that may be attributed to a unit concentration of each organic and inorganic aquatic component), the impacts of suspended organic, suspended inorganic, and dissolved organic matter on the dominant wavelengths of natural water masses is illustrated. A model is proposed to explain water colour variations in British Columbia river systems based upon elevation, drainage area, glacial-feed, groundwater intrusion, turbidity, and complexity of input sources. It is shown that simple sub basins which are alpine and runoff-dominated generally display dominant wavelengths in the wavelength interval 480 - 550 nm (i.e. colours usually perceived by the human eye to be in the range blue to turquoise), a consequence of low to moderate turbidity comprised predominantly of suspended inorganics. Simple sub basins which are groundwater-dominated 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 low to high turbidity comprised of both dissolved organics and suspended inorganics. Most of the Canadian Cordillera is comprised of complexes of sub basins and, as such, necessitate integration of a variety of inputs. These complexes are shown to display dominant wavelengths in the restricted wavelength interval 573 - 578 nm. This "spectral colour saturation" results in such river water being perceived by the human eye to be brownish in colour.

RÉSUMÉ

Des spectres de réflectance volumique sous la surface, dans la plage comprise entre 400 et 740 nm, ont été mesurés directement à quatre occasions différentes, en 1986 et 1987, au niveau de chacune des quatorze stations hydrographiques en Colombie-Britannique. Des analyses de la chromaticité ont été effectuées sur ces spectres continus de réflectance afin de déterminer la couleur de l'eau en fonction d'une longueur d'onde dominante et de la pureté qui y est associée. À l'aide de la notion de "vues en coupe optiques" (mesure des ondes de dispersion et d'absorption qui peut être attribuée à une unité de concentration de chaque composante organique et inorganique de l'eau), on illustre les répercussions des matières organiques en suspension, des matières inorganiques en suspension et des matières organiques dissoutes sur les longueurs d'onde dominantes des masses d'eau naturelles. Pour expliquer les variations colorimétriques de l'eau dans des réseaux hydrographiques de la Colombie-Britannique, on propose un modèle sur l'altitude, la superficie du bassin, l'alimentation par l'eau de fonte des glaciers, l'intrusion des eaux souterraines, la turbidité et la complexité des sources d'alimentation. On a montré que dans des bassins secondaires simples, dominés par l'eau de montagne et l'eau de ruissellement, les longueurs d'onde dominantes se situent en général entre 480 et 550 nm (c'est-à-dire les couleurs perçues en général par l'oeil humain dans la gamme du bleu au turquoise), résultant d'une turbidité de faible à modérée causée surtout par la présence de matières inorganiques en suspension. Dans des bassins secondaires simples, alimentés surtout par des eaux souterraines, les longueurs d'onde dominantes se situent entre 550 et 570 nm (c'est-à-dire, les couleurs perçues dans la gamme du vert au brun), résultant d'une turbidité de faible à élevée causée par des matières organiques dissoutes et des matières inorganiques en suspension. La plus grande partie de la Cordillère canadienne est composée de complexes de bassins secondaires et, de ce fait, il faut intégrer diverses sources d'alimentation. Dans ces complexes, les longueurs d'onde dominantes se trouvent dans l'intervalle restreint de 573 à 578 nm. En raison de cette saturation de la couleur spectrale dans le cas d'une rivière de ce genre, l'oeil humain perçoit l'eau comme brunâtre.

INTRODUCTION

The observed colour of a natural water body is a direct consequence of the interaction of the incident downwelling sky and solar irradiance with the optically-active organic and inorganic components of that water. The colour of water has often been considered to represent, in addition to one's initial aesthetic impression of the water, an indication of the quality of that water body. Indeed, as shown in great detail elsewhere (Bukata et al., 1981; 1985), determination of the degree of scattering and absorption per unit concentration of each of the principal organic and inorganic components of natural waters as a function of wavelength can enable direct measurements of the observed water colour to be used to estimate such water quality indicators.

Since water masses display both spatial and temporal variations in their organic and inorganic compositions, it logically follows that they will be characterized by related variabilities in their observed interactions with the impinging radiation field. 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.

DIRECT OPTICAL MEASUREMENTS AND CHROMATICITY ANALYSES

From the perspective of the human observer, colour is the effect of the interplay between the light spectrum reaching the eye and the eye's spectral response. The human eye is trichromatic, i.e. it responds to the three spectral regions red, green, and blue. Thus, any perceived colour can be created by appropriately proportioning red, green, and blue light. Such apportionment of white light into its tristimulus red, green, and blue components forms the basis of chromaticity analyses.

Neglecting surface reflection (which can often mask a water's true colour), the colour of a natural water body is determined by its optical properties, particularly by the scattering and absorption coeffients which quantify the number of scattering and absorption events that photons undergo in their underwater propagation. As shown by Jerome et al. (1988), the colour of light reflected back through the air/water interface can be obtained from the subsurface volume reflectance spectrum R(λ), which is related to the scattering and absorption coefficients by the mathematical expressions

$$R(\lambda) = 0.319 \frac{B(\lambda)b(\lambda)}{a(\lambda)} \quad \text{for } 0 < \frac{Bb}{a} < 0.25 \qquad (1)$$

$$R(\lambda) = 0.267 \frac{B(\lambda)b(\lambda)}{a(\lambda)} + 0.013 \quad \text{for } 0.25 < \frac{Bb}{a} < 0.50 \qquad (2)$$

where a = absorption coefficient (m^{-1})

b = scattering coefficient (m^{-1})

B = backscattering probability.

The optical coefficients a, b and B are generally controlled by three naturally-occurring aquatic components, viz. the dissolved organic matter, suspended organic matter, and suspended inorganic matter. The dissolved organic matter may be monitored by measuring the concentration of dissolved organic carbon (DOC), the suspended organic matter by measuring the concentration of chlorophyll, and the suspended inorganic matter by measuring the concentration of suspended mineral. Together the suspended and dissolved matter can also be related to turbidity.

If the spectral values a(λ), b(λ) and B(λ) are known for each of the organic and inorganic aquatic components, then the volume reflectance of a water body containing any combination of these components can be predicted (Bukata et al., 1983; 1985). By incorporating this subsurface volume reflectance with a standard incident solar spectrum, the light upwelling from the water may be calculated. This upwelling light from beneath the air/water interface coupled with the incident radiation reflected by the air/water interface combine to produce the total radiation upwelling from natural waters.

In this study the optical measurements were performed _in situ_ to eliminate the effects of surface reflection and to directly measure the volume reflectance of the water R(λ). These subsurface R(λ) spectra were then combined with an incident radiation spectrum for a standard atmosphere taken from Kondratyev (1969) to obtain an upwelling irradiance spectrum E(λ) for each station and each sampling date.

These measured/calculated upwelling irradiance spectra E(λ) were related to a perception of visual colour through chromaticity analyses which integrate the sensitivity of the human eye with an impinging energy spectrum. Such an integration produces tristimulus values X', Y' and Z', from which the chromaticity coordinates X (red), Y (green), and Z (blue) may be obtained.

Following the CIE (Anonymous, 1957) standard colorimetric system the tristimulus values of an upwelling irradiance spectrum E(λ) are given by

$$X' = \int E(\lambda)\, x(\lambda)\, d\lambda \qquad (3)$$

$$Y' = \int E(\lambda)\, y(\lambda)\, d\lambda \qquad (4)$$

$$Z' = \int E(\lambda)\, z(\lambda)\, d\lambda \qquad (5)$$

where x(λ), y(λ) and z(λ) are the CIE colour mixtures (for red, green and blue, respectively) for equal energy spectra and may be obtained from CIE tables (Jerlov, 1976).

The chromaticity coordinates X, Y and Z (for red, green and blue, respectively) are readily defined by the ratios

$$X = X' / (X' + Y' + Z') \qquad (6)$$

$$Y = Y' / (X' + Y' + Z') \qquad (7)$$

$$Z = Z' / (X' + Y' + Z') \qquad (8)$$

Since X + Y + Z = 1, two chromaticity coordinates adequately represent colour in a chromaticity diagram. Consequently, the chromaticity diagrams for the British Columbia river stations will be displayed as rectangular plots of Y (green) and Z (blue).

Using the CIE colour mixture values, x(λ), y(λ), z(λ) and assuming monochromatic light of a given wavelength as the spectrum E(λ), the CIE chromaticity coordinates may be obtained for that particular wavelength. By continuing this procedure, a complete set of CIE chromaticity coordinates may be obtained for each wavelength throughout the visible spectrum. All the (Z, Y) pairs obtained in such a manner are plotted in Figure 2. The loci of these (Z, Y) pairs defines an envelope which encompasses all possible chromaticity values. For a "white" spectrum (i.e. $E(\lambda)$ = constant) X = Y = Z = 0.333. This defines the achromatic colour or white point S illustrated in Figure 2. A numerical value of colour is then obtained by drawing a line from this white point S through the plotted chromaticity values of the measured spectrum (as indicated by the point C). The intersection of the line S-C with the curve envelope of Figure 2 (indicated by point L) specifies the dominant wavelength of the observed spectrum. It is this dominant wavelength that will be herein considered as the colorimetric definition of the natural water body.

The distinctiveness of this dominant wavelength is termed "purity" and is defined in Figure 2 as the ratio of the line C-S to the line L-S. Purity thus represents a resolution of the dominant wavelength within an observed optical spectrum. A purity of 1.0 would indicate a monochromatic beam at the dominant wavelength, while a purity of 0 would indicate an inability to resolve the wavelength from a "white" background spectrum.

VOLUME REFLECTANCE SPECTRA OF BRITISH COLUMBIA 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 Figures 3 - 7 which display 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), 11 (Bull River at the Hatchery), and 14 (Fraser River at Hope) respectively. From the measured volume reflectance spectra it was noted that:

a) The Kettle River (stations 3 and 4) was characterized by very low volume reflectance values (<3%).

b) Very high volume reflectance values (15-20%) were observed in the Kootenay River at Canal Flats (station 8) and in the Bull River at the Hatchery (station 11).

c) High volume reflectance values (>10%) were observed in the Columbia River at Donald (station 5), in the Kootenay River at Fenwick (station 9) and in the Fraser River at Hope (station 14).

d) The remainder of the British Columbia river stations displayed volume reflectance values in the 4% to 10% range.

e) The peak of the measured subsurface volume reflectance occurred between 550 nm and 600 nm for all stations (summer and fall) with the following exceptions:

    1) Kootenay River at Canal Flats (station 8) which displayed a peak reflectance at 470 nm in the fall of 1987.

    2) Kootenay River at Fenwick (station 9) which displayed a peak reflectance at 630 nm in the summer of 1986.

    3) Bull River at the Hatchery (station 11) which displayed a peak reflectance at 540 nm in the fall of 1987.

    4) Elk River at Highway 93 (station 12) which displayed a peak reflectance at 610 nm in the summer of 1986.

5) Fraser River at Hope (station 14) which displayed a peak reflectance at 610 nm in the summer of 1986 and at 640 in the summer of 1987.

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%) 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 WATERS

Using measured volume reflectance spectra and an incident radiation spectrum for a standard clean, dry atmosphere taken from Kondratyev (1969), upwelling irradiance spectra were obtained for each station and sampling date. Chromaticity coordinates for each upwelling spectra were then calculated in the manner described above. Figures 8 and 9 illustrate chromaticity plots for stations 4 (Kettle River at Gilpin) and 14 (Fraser River and Hope), respectively. Also shown on Figures 8 and 9 are the white point and the curve envelope. An analysis of all fourteen stations showed that:

a) The points for a station are often closely clustered, eg. Kettle River at Gilpin (station 4) and Columbia River at Trail (station 7).

b) The points for a station are often positioned along a line extending from the white point to the enveloping curve, eg. Kettle River at Midway (station 3) and Fraser River at Hope (station 14).

From such chromaticity plots the dominant wavelengths along with their purity were determined for each upwelling spectrum for each station and each visit. These calculated dominant wavelengths and purity values are listed in Table 2. Two sets of entries are given for each station, namely the dominant wavelength observed in the summer and the dominant wavelength observed in the fall. The upper line records the 1986 values while the lower line records the 1987 results at each station.

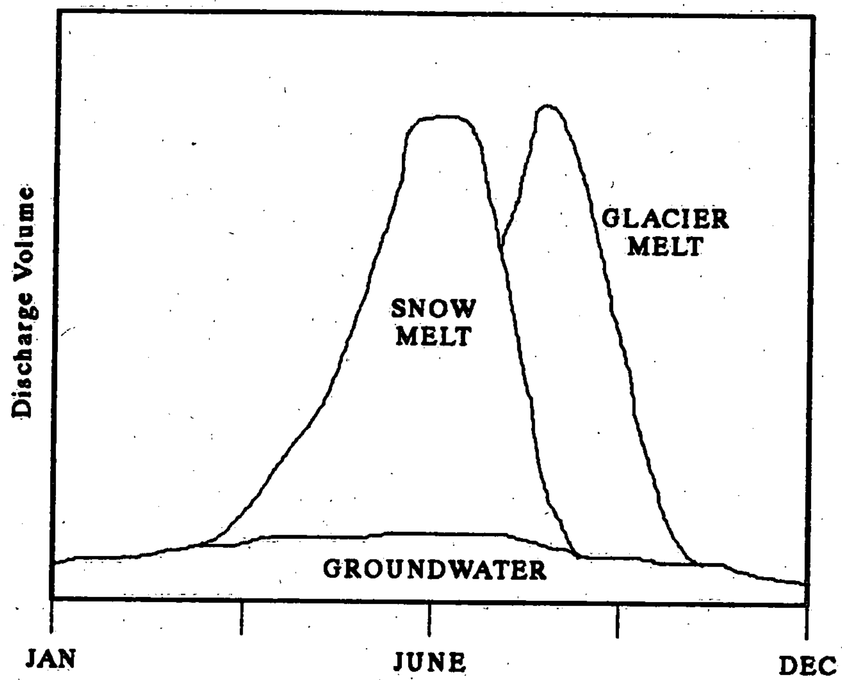
Also included within Table 2 are turbidity values for each river station. Turbidity values were not obtained with the October 1986 optical data set. However, data from the regular Water Quality Branch Survey are listed in Table 2 when the Survey samples were obtained within a 24 hour period of the October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

DISCUSSION OF OBSERVATIONS

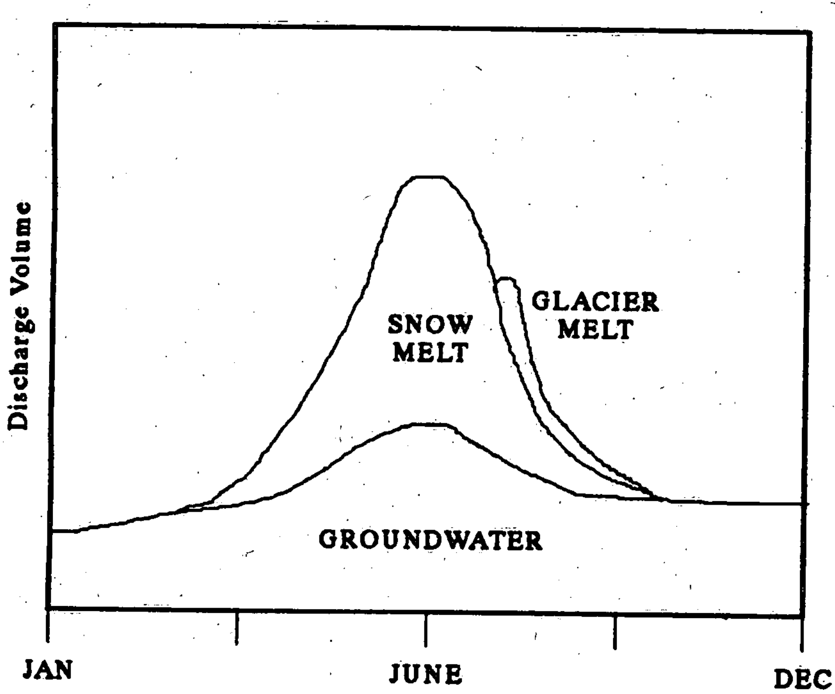
Glacier dynamics has accounted for much of the temporal evolution of the British Columbia landforms which display ubiquitous consequences of glacial ice erosion and deposition. Of the fourteen stations studied in the current work, eight are more responsive to glacial melt intrusions (the 3 Columbia River 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 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 in Figure 10. 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 10. The role of groundwater for stations responsive to both snowmelt and glacial melt, is distinctly less significant to 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 are 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 display a stronger likelihood of optically responding to a dissolved organic component than do glacier-fed stations.

Hence, summer optical spectra may be considered to represent river water comprised predominantly of snow melt at glacier-fed stations, and some combination of snowmelt and groundwater at non glacier-fed stations. That is, summer subsurface volume reflectance



GLACIER-FED RIVER STATIONS



NON GLACIER-FED RIVER STATIONS

FIGURE 10

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 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 10 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 11 schematically illustrates a river basin that would require such integration from a multitude of sources.

Therefore, it would be logical to classify the British Columbia river stations as belonging to one of three classifications, namely:

a) runoff-dominated

b) groundwater-dominated

c) complex (i.e. a consequence of integrated sources)

The salient features of the data contained in Tables 2 and 3 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 sampling at 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. 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 complex river station classification due to the many tributaries of the Columbia River.

2. Very little variation ($\leq$ 7 nm) was seen between the two summer determinations at nearly all the river stations. Neglecting bottom effects only stations 9 and 11 displayed slightly larger variations, and even then variations were $\leq$ 10 nm.

3. 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 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.

4. For each non glacial-fed river station the summer and fall dominant wavelengths were numerically similar, displaying a difference of no more than 9 nm.

5. 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. Again, as explained earlier, an exception to this behavior pattern is the station at the Donald.

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.

INFLUENCE OF THE COMPONENTS OF A WATER BODY ON ITS DOMINANT WAVELENGTH

The perceived colour of a natural water body is directly controlled by the scattering and absorption processes occurring within that natural water body. The direct linkages between the component scattering and absorption centres and the measured subsurface volume reflectance spectra are the specific scattering and absorption coefficients per unit concentration of each aquatic component. Thus, to evaluate and fully interpret the optical results listed in Table 2, such "optical cross sections" (Bukata et al. 1985) should be determined for each organic and inorganic component present within the British Columbia river systems. Such a large scale data collection mission was beyond the scope of the present study. However, such a program conducted in Lake Ontario (Bukata et al., 1981; 1985) has resulted in optical cross sections appropriate to Lake Ontario water masses. These optical cross sections (determined for suspended minerals, chlorophyll, and dissolved organic carbon) are undoubtedly inappropriate for British Columbia river waters. Nonetheless, they may serve as a basis for explaining the differences in colours observed in the British Columbia river waters.

As shown in equations (1) and (2) the subsurface volume reflectance $R(\lambda)$ can be determined from the backscattering and absorption coefficients $B(\lambda)b(\lambda)$ and $a(\lambda)$ appropriate to the water body under consideration. Further, $B(\lambda)b(\lambda)$ and $a(\lambda)$ may themselves be expressed in terms of the aquatic components, viz.

$$a(\lambda) = \sum a_i(\lambda)x_i \tag{9}$$

$$B(\lambda)b(\lambda) = \sum B_i(\lambda)b_i(\lambda)x_i \tag{10}$$

where $a_i(\lambda)$ and $B_i(\lambda)b_i(\lambda)$ represent the optical cross sections (ie. the absorption coefficient and backscattering coefficient per unit concentration of the ith aquatic component at wavelength λ), and x_i represents the concentration of the ith component.

Knowing the optical cross sections, therefore, enables the subsurface volume reflectance spectrum $R(\lambda)$ to be generated for any combination of aquatic component concentrations. Once such $R(\lambda)$ are generated, upwelling irradiance spectra $E(\lambda)$ may be readily generated upon which the CIE chromaticity analyses may be performed. Using Lake Ontario optical cross sections, dominant wavelengths were determined for various combinations of chlorophyll, suspended minerals and dissolved organic carbon. The results of such theoretical analyses are depicted in Figures 12 - 14.

Figure 12 illustrates the family of relationships between dominant wavelength and suspended mineral concentration for a water mass in which the dissolved organic carbon is kept fixed at zero while the concentration of chlorophyll is varied between 0 and 20 μg/l.

Figure 12 shows that low (<480 nm) dominant wavelengths can be recorded for very low turbidity values. Values of suspended mineral > ~ 3.5 mg/1 result in dominant wavelength values > ~ 550 nm even in the absence of both chlorophyll and DOC. Similarly, concentrations of chlorophyll > ~ 7.0 µg/1 result in high values of dominant wavelength even in the absence of suspended mineral.

Figure 13 illustrates the family of relationships between dominant wavelength and dissolved organic carbon concentration for a water mass in which the chlorophyll concentration is kept fixed at zero while the concentration of suspended mineral is varied between 0 and 20 mg/1. It is interesting to note that in the absence of suspended mineral and chlorophyll concentrations (curve A), the dominant wavelength remains relatively unaltered despite the amount of DOC present in the water. Large concentrations of suspended mineral (Curves G, H, I) completely overwhelm the optical impact of the DOC and once again the dominant wavelength is unaltered by the DOC concentrations. Intermediate values of suspended mineral (0.1 mg/1 to 2.0 mg/1) are required to visually distinguish the colour impact of variable DOC concentrations. This is a consequence of the fact that a natural water body must contain effective scattering centres to produce perceived water colour variations. Dissolved materials are generally not effective light scatterers. Both suspended minerals and chlorophyll are effective scatterers, and a similar impact of chlorophyll concentrations on DOC will be evident in the next figure. Figure 13 once again illustrates that a low value of dominant wavelength requires a low concentration of suspended mineral.

Figure 14 illustrates the family of relationships between dominant wavelength and dissolved organic carbon concentration for a water mass in which the suspended mineral concentration is kept fixed at zero while the concentration of chlorophyll is varied between 0 and 20 µg/1. The role of chlorophyll concentrations in distinguishing the impact of DOC on dominant wavelength is similar to the role of suspended mineral in this regard. Intermediate concentrations of chlorophyll (0.5 µg/1 to 5.0 µg/1) are required to display the colour impact of DOC in the absence of suspended mineral. The features of the subsurface optical spectra observed in this study are not inconsistent with the nature of Figures 12 - 14 namely:

1. Low turbidity (i.e. simultaneously low concentrations of suspended mineral and chlorophyll) will result in upwelling irradiance spectra $E(\lambda)$ characterized by low values of dominant wavelengths, provided the dissolved organic carbon concentration is also low (as expected for glacier-fed, runoff-dominated river stations);
2. Low turbidity waters may, however, display upwelling irradiance spectra characterized by high values of dominant wavelengths if substantial concentrations of dissolved organic material is present (as expected for groundwater-dominated river stations);
3. High turbidity concentrations result in high values of dominant wavelengths (as is possible for any station be it runoff-dominated, groundwater-dominated or some integrated consequence of several sources).

Clearly, the optical cross sections pertinent to British Columbia river waters must be determined. This is evident from the fact that glacier-fed stations display waters that are predominantly comprised of snowmelt water in the summer and glacial-melt water in the fall.

Non glacier-fed stations display waters that are comprised of a combination of snowmelt and groundwater in the summer and predominantly groundwater in the fall. Consequently, different combinations of suspended inorganic and dissolved organic materials are anticipated at each river station. The optical properties (i.e. cross sections) of the indigenous aquatic components dictate the upwelling irradiance spectra. Hence, detailed coordinated programs of in situ spectral measurements and water quality sampling surveys are required to obtain such obligatory optical cross sections. Once such cross sections are reliably determined, direct measurements of upwelling irradiance spectra may be utilized, along with mathematical optimization techniques, to determine the general composition of British Columbia river waters.

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 mass at the time of observation, the dominant wavelength can logically be expected to be dependent upon those basin parameters and/or activities that dictate aquatic composition. In addition to groundwater and surface runoff, 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 water. Possible relationships among British Columbia river water colour and these basin parameters were explored.

Figure 15 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 15 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 15 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 optical 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 15 are the glacier-fed stations. Since the elevation of a station varies inversely with its proximity to glaciers, the relationship of Figure 15 is consistent with the runoff-dominated hydrograph of Figure 10. Further, as seen from Figure 15, 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 seen from Figures 12 and 13, low values of dominant wavelength are associated with aquatic regimes containing small concentrations of suspended inorganic material. This suggests that glacial runoff 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 mineral in Lake Ontario) or possibly intermediate turbidity values (if the suspended mineral in the glacial runoff are characterized by a flat, i.e. "white" optical cross section spectrum). In either case, Figures 10, 12, 13 and 15 appear to be in good agreement.

There is evidence to support the possibility that a "white" optical cross section spectrum may indeed define the glacial feed. Low values of the chromaticity purity (as seen from Table 2) are generally observed for glacial-fed stations. Also, the very high values of volume reflectance observed in the glacier-fed stations Canal Flats (Figure 5) and the Hatchery (Figure 6) 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 16 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 classification. Such integrated source stations would tend to be characterized by water masses 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.

PROPOSED MODEL FOR INTERPRETING COLOURS OF CORDILLERAN RIVER WATER

The Canadian Cordillera, like most large basin regions, 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 runoff-dominated

Type 2: Simple sub basins which are predominantly groundwater-dominated

Type 3: Complex sub basins which are integrations of a multitude of Type 1 and/or Type 2 sub basins.

For the Cordillera, Type 1 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 are almost exclusively of the tertiary watershed variety.

Type 2 may be defined as having the following properties: lower elevations, large or small drainage areas, minimal influence from glacial runoff, substantial influence from snowmelt runoff and from groundwater intrusion, low to high turbidity values, and relatively constant upper and lower limits of dominant wavelength. These Type 2 sub basins could be either of the secondary or tertiary watershed variety.

Type 3 (since it is a consequence of a dendritic system such as illustrated in Figure 11) may be defined by any combination of the physical basin parameters (elevation, drainage area, source waters, impoundments) defining Types 1 and 2. However, Type 3 has its own specific optical signature, namely, a restricted range of dominant wavelengths (~ 573 - 578 nm). The Type 3 sub basin complexes comprise the principal watersheds of large basin systems, and stations of this Type represent the majority of stations listed in Table 1.

An appropriate water colour model would then attempt to relate a volume reflectance history at a station to the classification Type of that station. In conclusion, therefore, we propose an optical model which would ascribe Type 1 sub basin water colour to mainly low to moderate values of suspended mineral concentrations associated with snowmelt or glacial melt runoff. This results in a wider range of lower limit dominant wavelengths being observed at high elevations and small drainage areas. Expressed simply, Type 1 alpine watersheds should generally display colours in the range blue to turquoise.

The proposed model ascribes Type 2 sub basin water colour to low to high concentrations of suspended mineral in conjunction with substantial dissolved organic materials associated with groundwater intrusion. This results in relatively constant upper and lower limits of dominant wavelengths associated with lower elevations and any size drainage basin. Expressed simply, Type 2 sub basins generally display colours in the range green to brown.

The proposed model ascribes Type 3 sub basin water colour to integrated inputs from several distinct sources. 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 upper limit of colour defined by dominant wavelengths of these values. This is consistent with the asymptotic values > 570 nm illustrated in Figures 12 and 13 (even though the optical cross sections appropriate to Lake Ontario were used in generating these figures). Such "spectral colour saturation" in the 573 - 578 nm dominant wavelength range could be attained in either of two possible ways: a) high concentrations of suspended mineral which dominate the optical properties of the river water or b) low concentrations of suspended mineral coupled with concentrations of chlorophyll and/or dissolved organic materials large enough to optically dominate the river water. Expressed simply, Type 3 stations display consistently brown colours.

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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 at U.S. Boundary	9180	652	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

Table 2. Dominant Wavelengths, 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	575	46	3.4	567	47	-
	at U.S. Boundary	569	43	0.8	549*	22	0.1
2	Okanagan River	563	28	1.0	573*	46	0.2
	at Oliver	575*	46	0.5	578*	59	0.4
3	Kettle River	578	26	1.5	582	59	2.6
	at Midway	580	63	0.3	578	57	0.1
4	Kettle River	576	53	1.4	575	57	0.5
	at Gilpin	573	53	0.5	571	55	0.3
5	Columbia River	-	-	-	571	36	-
	at Donald	575	37	1.5	569	22	0.3
6	Columbia River	-	-	-	540	17	-
	at Revelstoke	562	31	8.9	553	26	1.0
7	Columbia River	567	16	1.5	-	-	-
	at Trail	574	17	0.5	570	20	0.3
8	Kootenay River	-	-	-	512	8	-
	at Canal Flats	558	13	13.0	489	20	0.2
9	Kootenay River	581	46	77.0	570	31	-
	at Fenwick Station	573	31	16.0	551	15	0.3
10	Kootenay River	571	46	1.2	566	42	2.4
	at Creston	570	46	0.8	554	27	0.3
11	Bull River	562	20	4.7	555	21	-
	at Hatchery	552	12	1.4	507	13	0.1
12	Elk River	572	21	125.0	574	37	-
	at Highway #93	572	29	0.5	548	10	0.1
13	Thompson River	-	-	-	572	47	1.9
	at Spences Bridge	568	42	2.2	573	49	0.3
14	Fraser River	576	28	43.0	579	61	10.0
	at Hope	574	17	32.0	575	44	1.6

* contains interference from bottom reflectance.

FIGURE CAPTIONS

Figure 1: British Columbia river sampling stations

Figure 2: The Y (green) and Z (blue) CIE chromaticity coordinates appropriate for each wavelength throughout the visible spectrum. The white point S is shown for Y = Z = 0.333. The points C and L are as defined in the text.

Figure 3: Subsurface volume reflectance spectra recorded at Station 3 (Kettle River at Midway).

Figure 4: Subsurface volume reflectance spectra recorded at Station 6 (Columbia River at Revelstoke).

Figure 5: Subsurface volume reflectance spectra recorded at Station 8 (Kootenay River at Canal Flats).

Figure 6: Subsurface volume reflectance spectra recorded at Station II (Bull River at the Hatchery).

Figure 7: Subsurface volume reflectance spectra recorded at Station 14 (Fraser River at Hope).

Figure 8: Chromaticity coordinate values for Station 4 (Kettle River at Gilpin).

Figure 9: Chromaticity coordinate values for Station 14 (Fraser River at Hope).

Figure 10: 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.

Figure 11: Schematic representation of a river station requiring the integration of hydrographs from multiple sources.

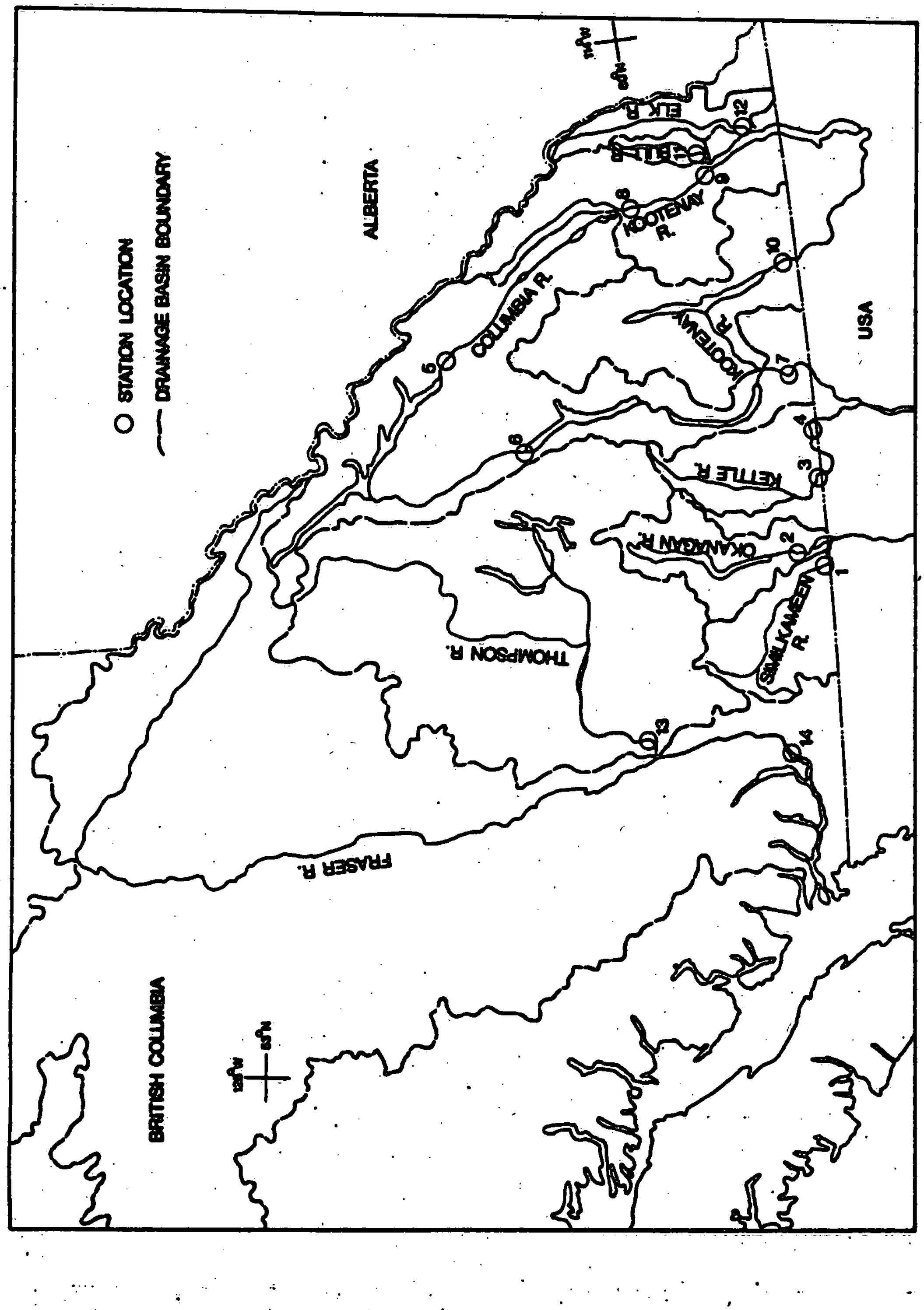
Figure 12: The family of relationships between dominant wavelength and suspended mineral concentration for a water mass in which the dissolved organic carbon is kept fixed at zero while the concentration of chlorophyll is varied between 0 and 20 μg/l.

Figure 13: The family of relationships between dominant wavelength and disolved organic carbon concentration for a water mass in which the chlorophyll concentration is kept fixed at zero while the concentration of suspended minerals is varied between 0 and 20 μg/l.

Figure 14: The family of relationships between dominant wavelength and dissolved organic carbon concentration for a water mass in which the suspended mineral concentration is kept fixed at zero while the concentration of chlorophyll is varied between 0 and 20 μg/l.

Figure 15: Range of dominant wavelengths observed at each river station plotted against the station elevation. Stations are numbered as in Table 1.

Figure 16: 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.



STATION LOCATION
DRAINAGE BASIN BOUNDARY
ALBERTA
BRITISH COLUMBIA
USA
ELK R.
KOOTENAY R.
COLUMBIA R.
KETTLE R.
OKANAGAN R.
SIMILKAMEEN R.
THOMPSON R.
FRASER R.
1
2
3
4
5
6
7
8
9
10
12
13
14

FIGURE 1

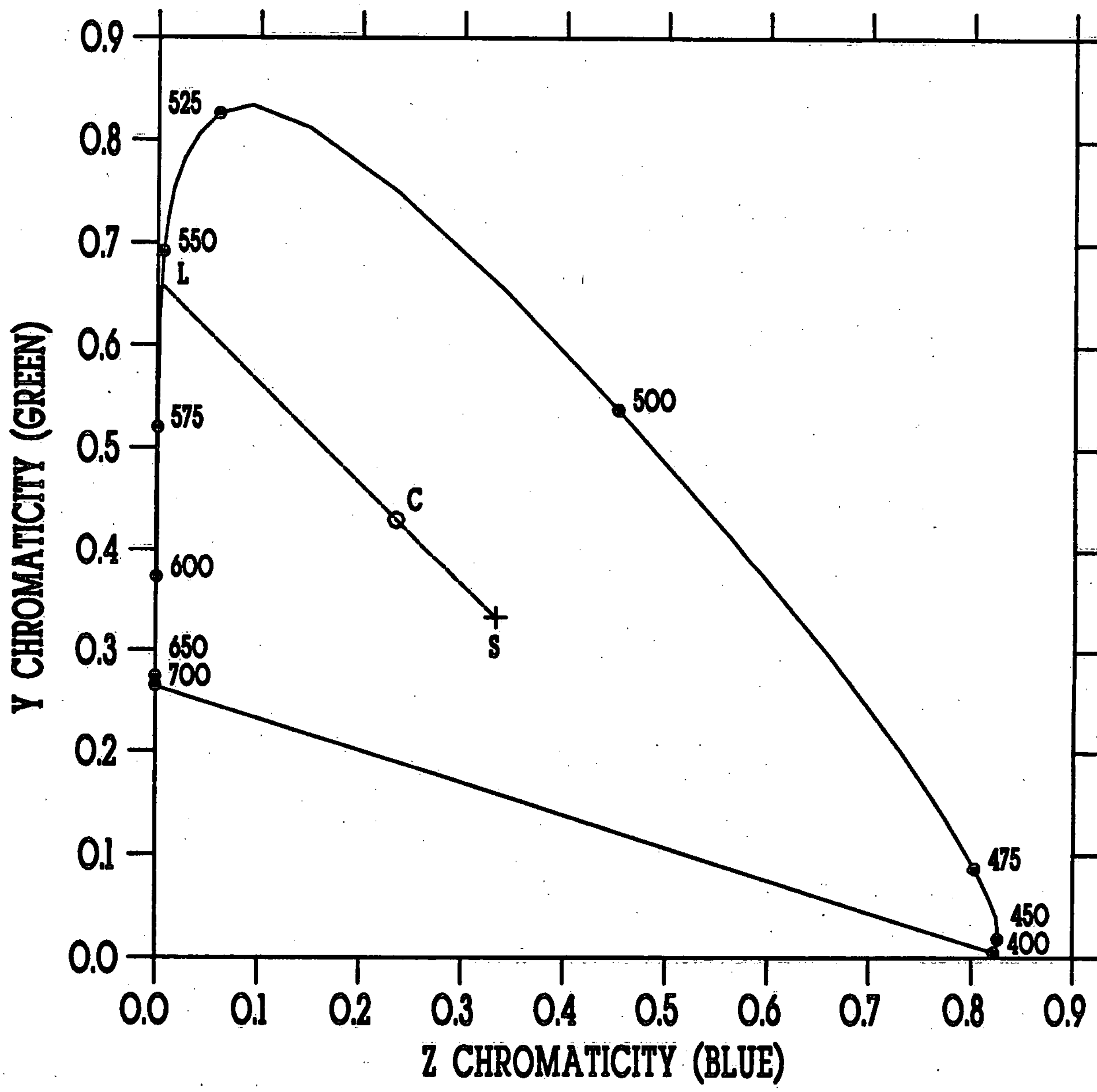

Y CHROMATICITY (GREEN)
Z CHROMATICITY (BLUE)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
525
550
L
575
600
650
700
500
C
S
475
450
400

FIGURE 2

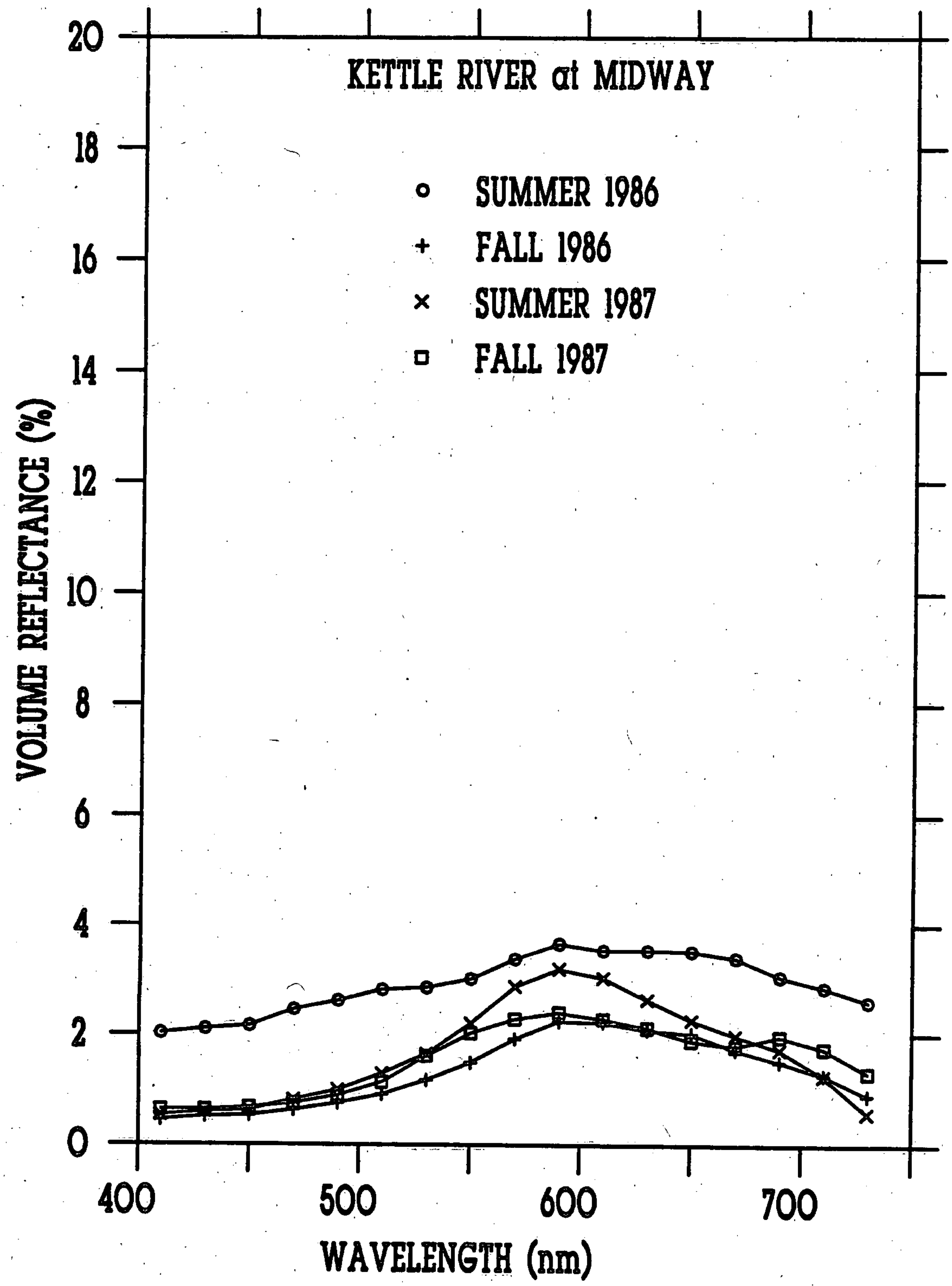

KETTLE RIVER at MIDWAY
SUMMER 1986
FALL 1986
SUMMER 1987
FALL 1987
VOLUME REFLECTANCE (%)
WAVELENGTH (nm)
0
2
4
6
8
10
12
14
16
18
20
400
500
600
700

FIGURE 3

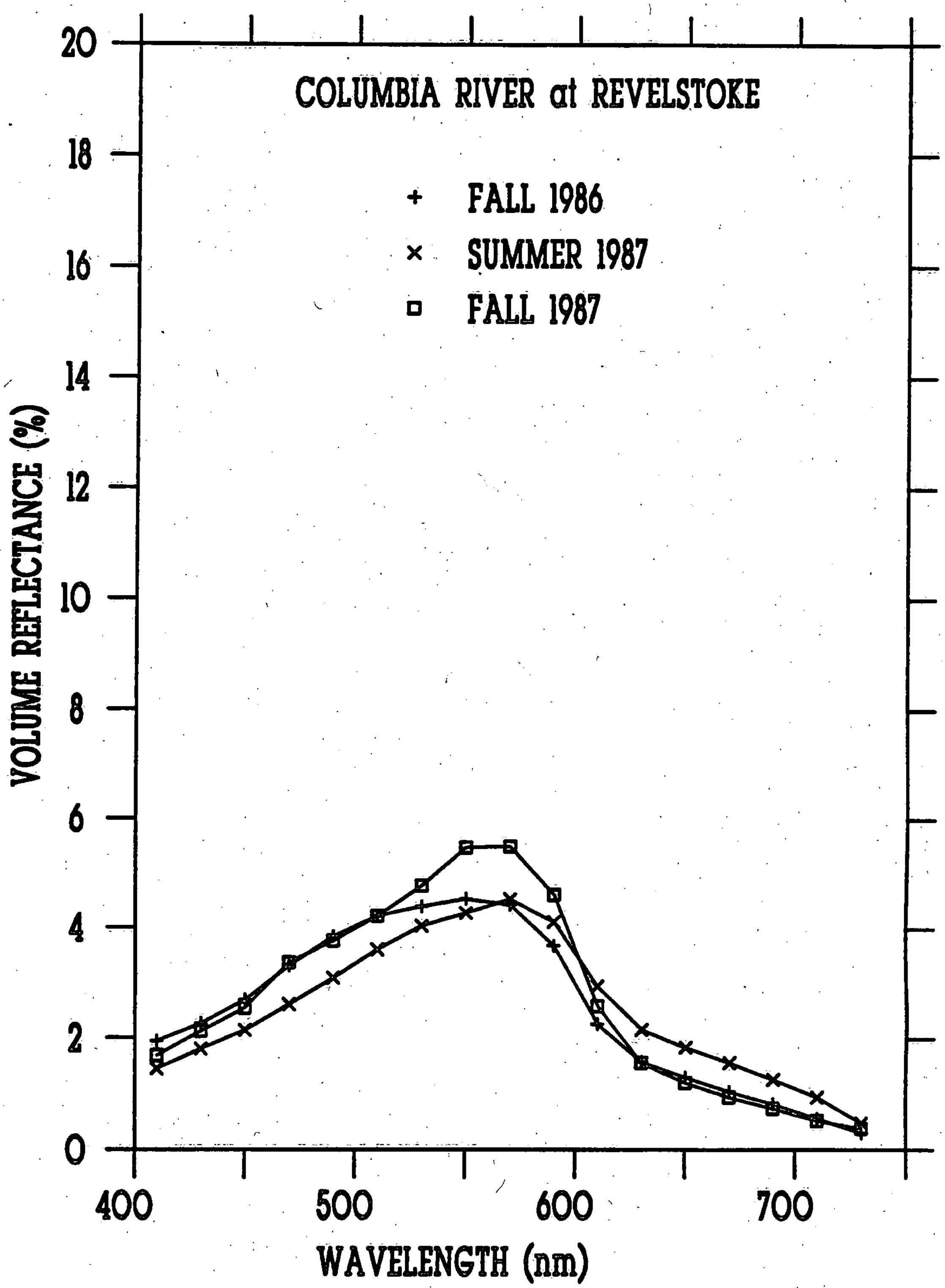
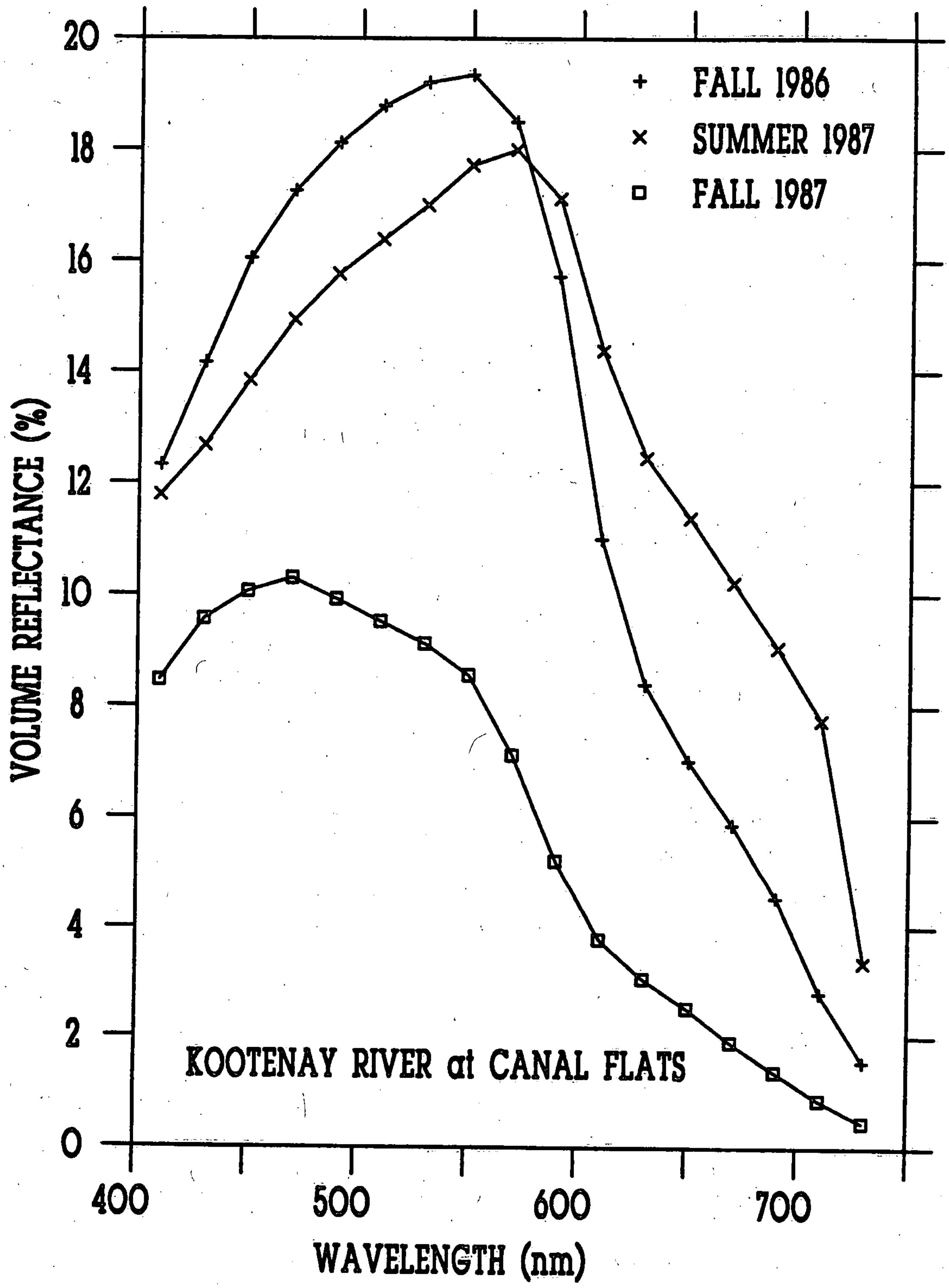
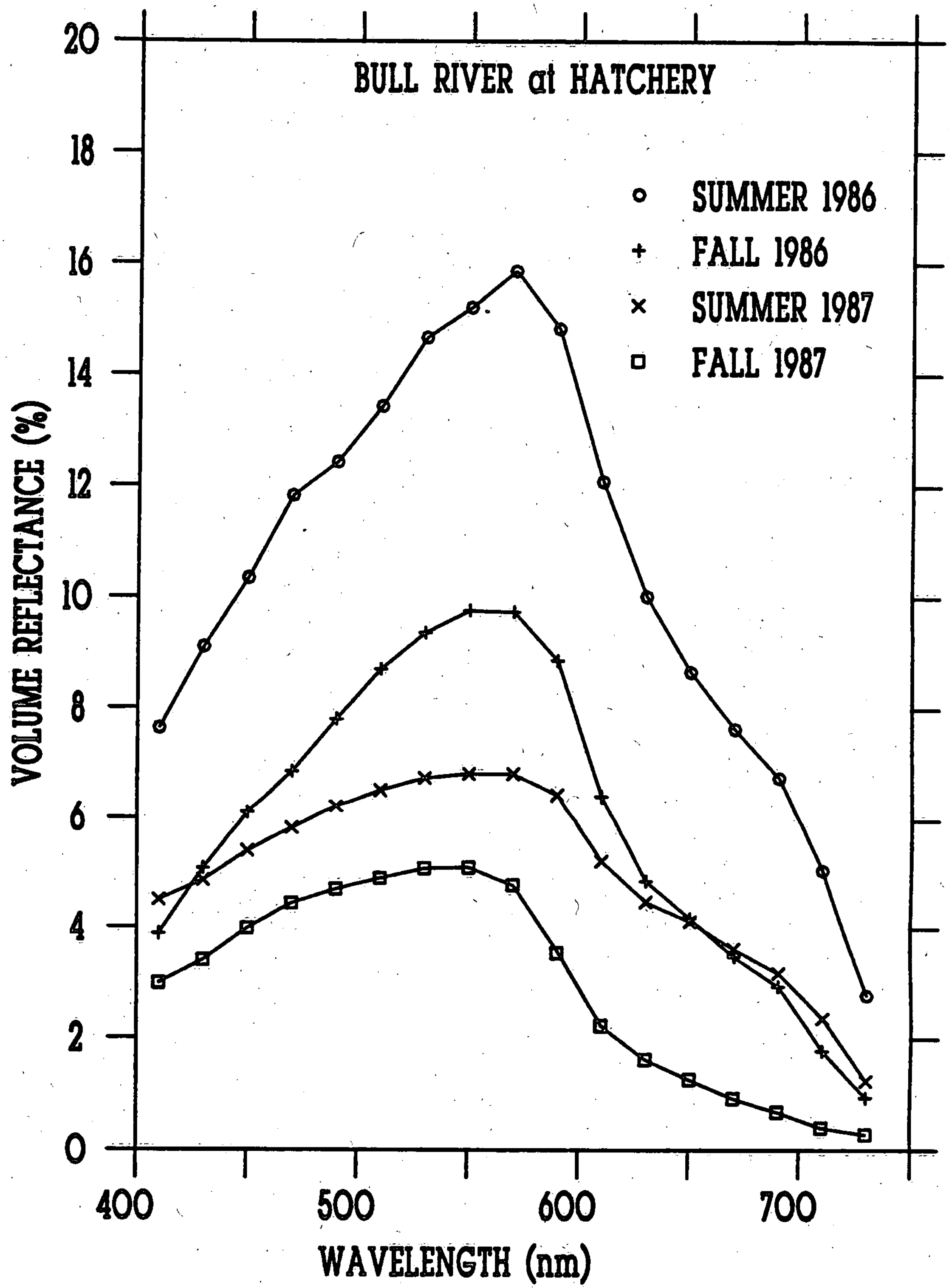

COLUMBIA RIVER at REVELSTOKE
FALL 1986
SUMMER 1987
FALL 1987
VOLUME REFLECTANCE (%)
0
2
4
6
8
10
12
14
16
18
20
400
500
600
700
WAVELENGTH (nm)

FIGURE 4



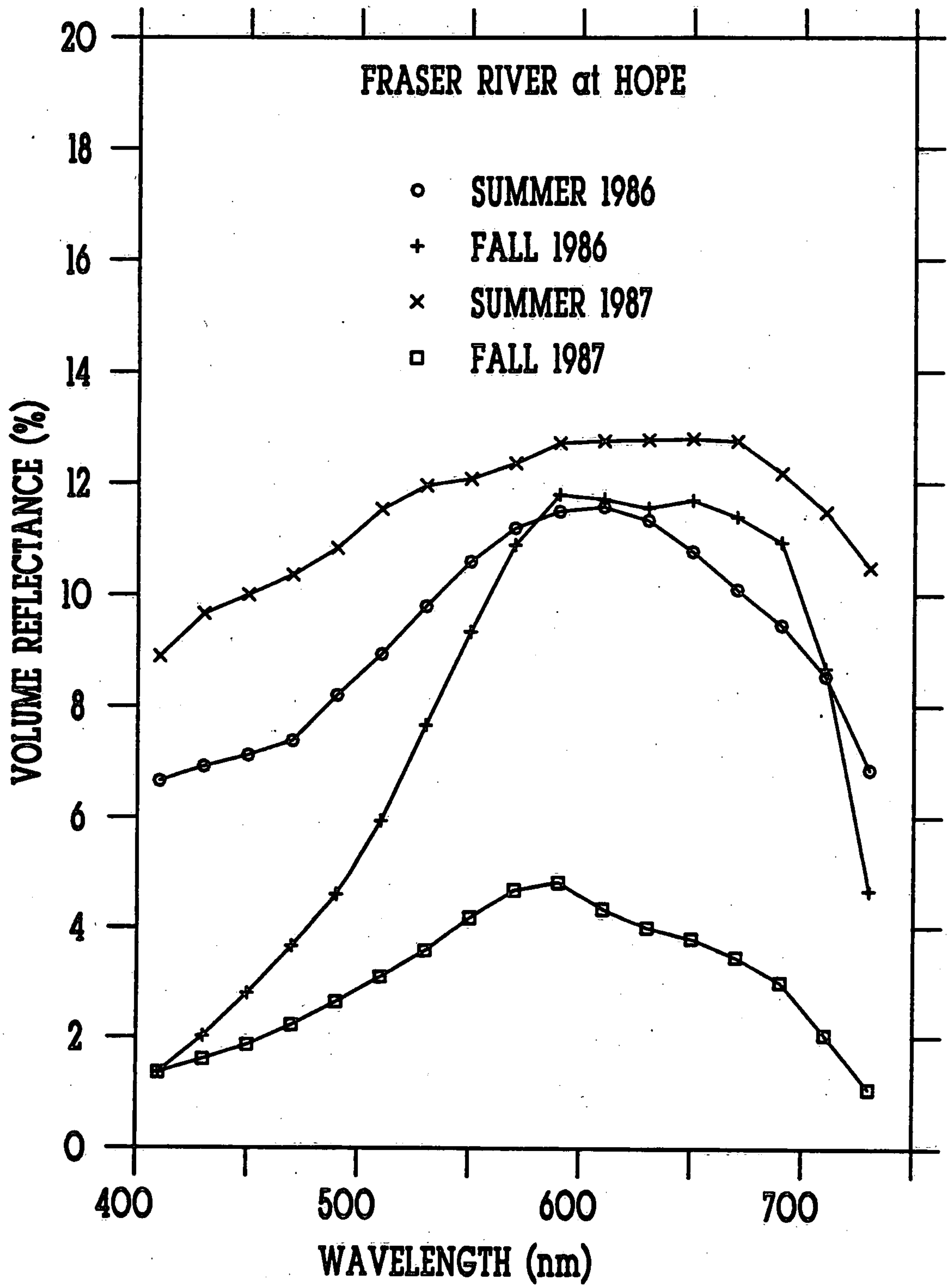
FALL 1986
SUMMER 1987
FALL 1987
KOOTENAY RIVER at CANAL FLATS
VOLUME REFLECTANCE (%)
WAVELENGTH (nm)
0
2
4
6
8
10
12
14
16
18
20
400
500
600
700

FIGURE 5



BULL RIVER at HATCHERY
SUMMER 1986
FALL 1986
SUMMER 1987
FALL 1987
VOLUME REFLECTANCE (%)
WAVELENGTH (nm)

FIGURE 6



FRASER RIVER at HOPE
SUMMER 1986
FALL 1986
SUMMER 1987
FALL 1987
VOLUME REFLECTANCE (%)
WAVELENGTH (nm)
0
2
4
6
8
10
12
14
16
18
20
400
500
600
700

FIGURE 7

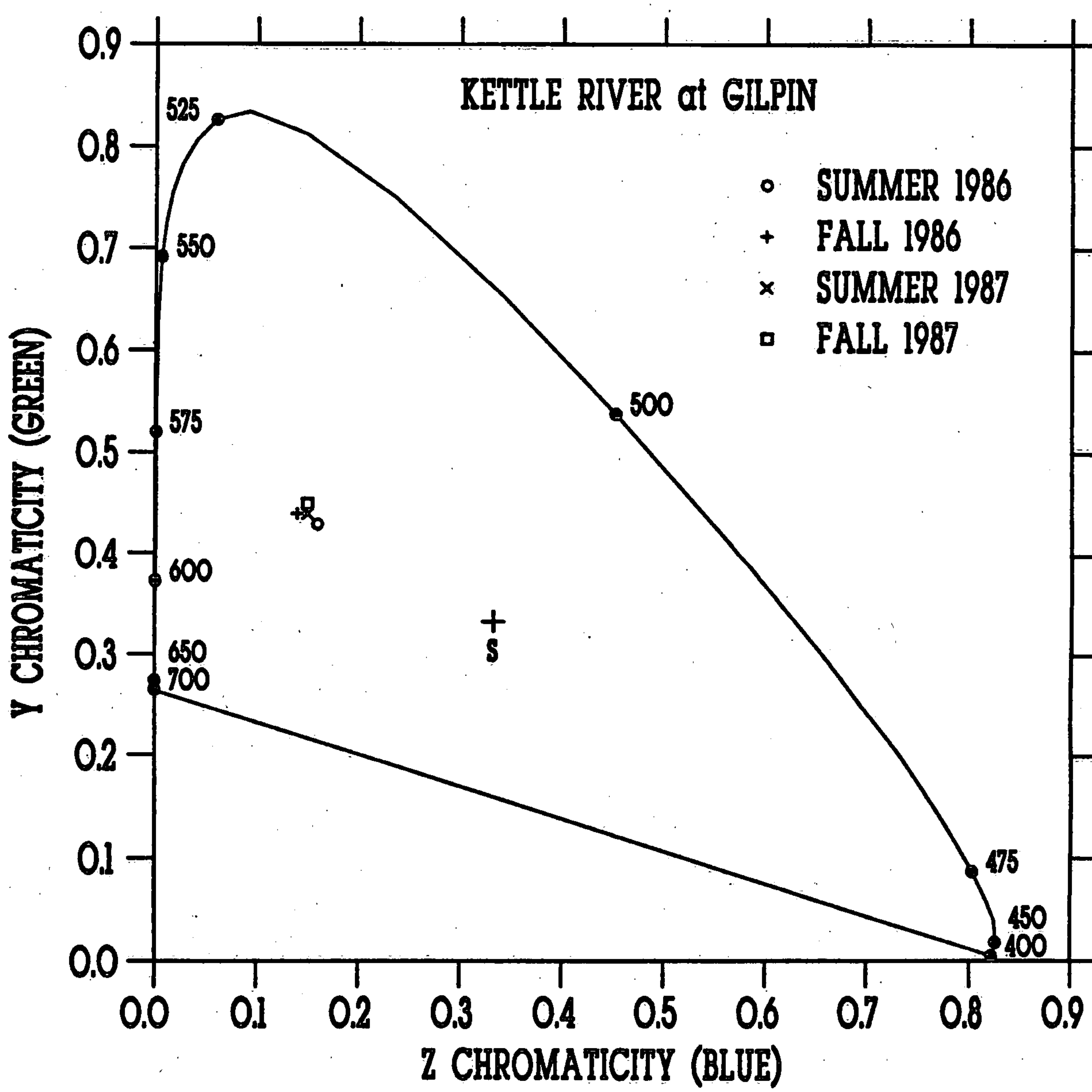

KETTLE RIVER at GILPIN
SUMMER 1986
FALL 1986
SUMMER 1987
FALL 1987
525
550
575
600
650
700
500
475
450
400
S
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Y CHROMATICITY (GREEN)
Z CHROMATICITY (BLUE)

FIGURE 8

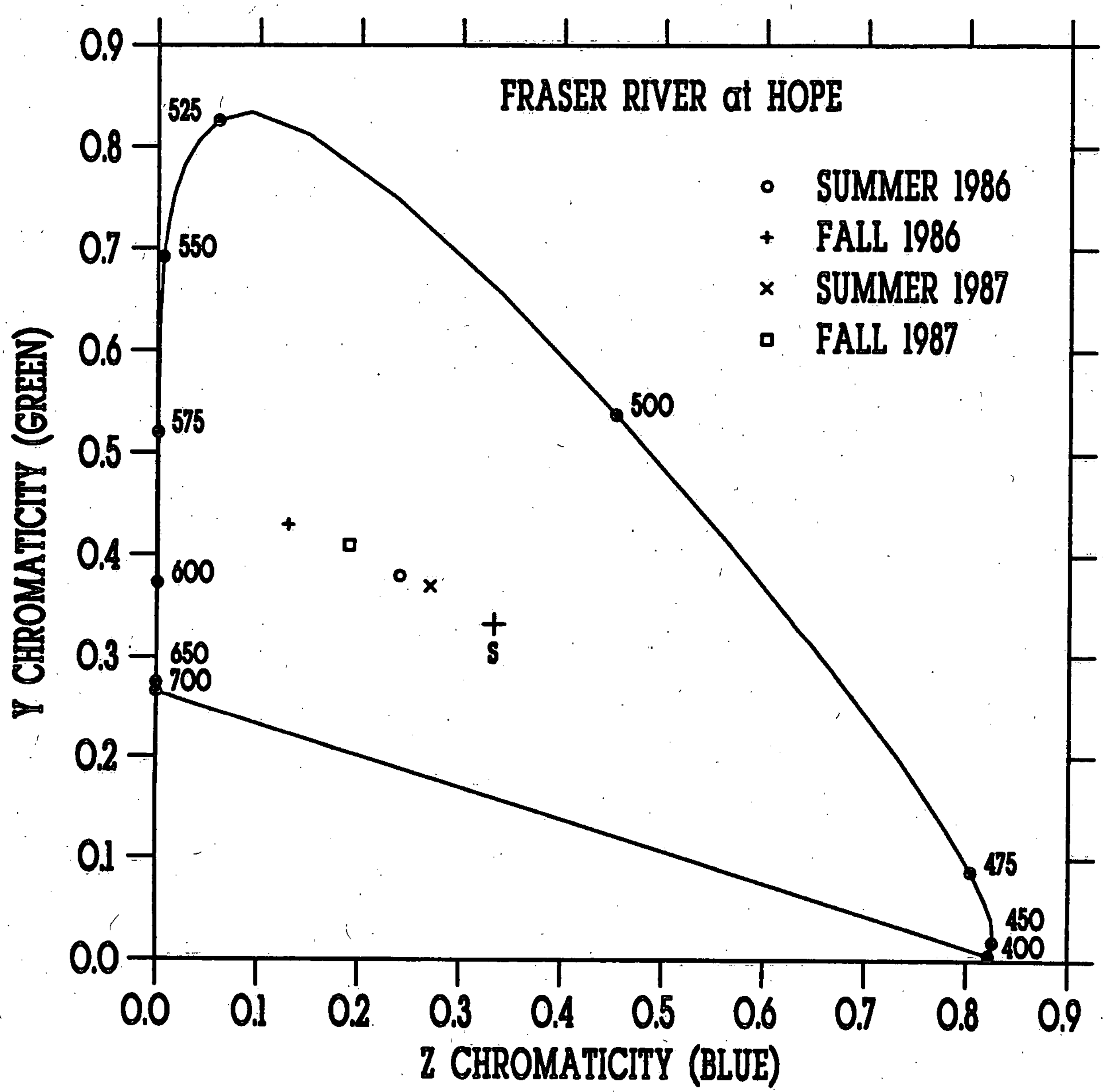

FRASER RIVER at HOPE
SUMMER 1986
FALL 1986
SUMMER 1987
FALL 1987
525
550
575
600
650
700
500
475
450
400
S
Y CHROMATICITY (GREEN)
Z CHROMATICITY (BLUE)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

FIGURE 9

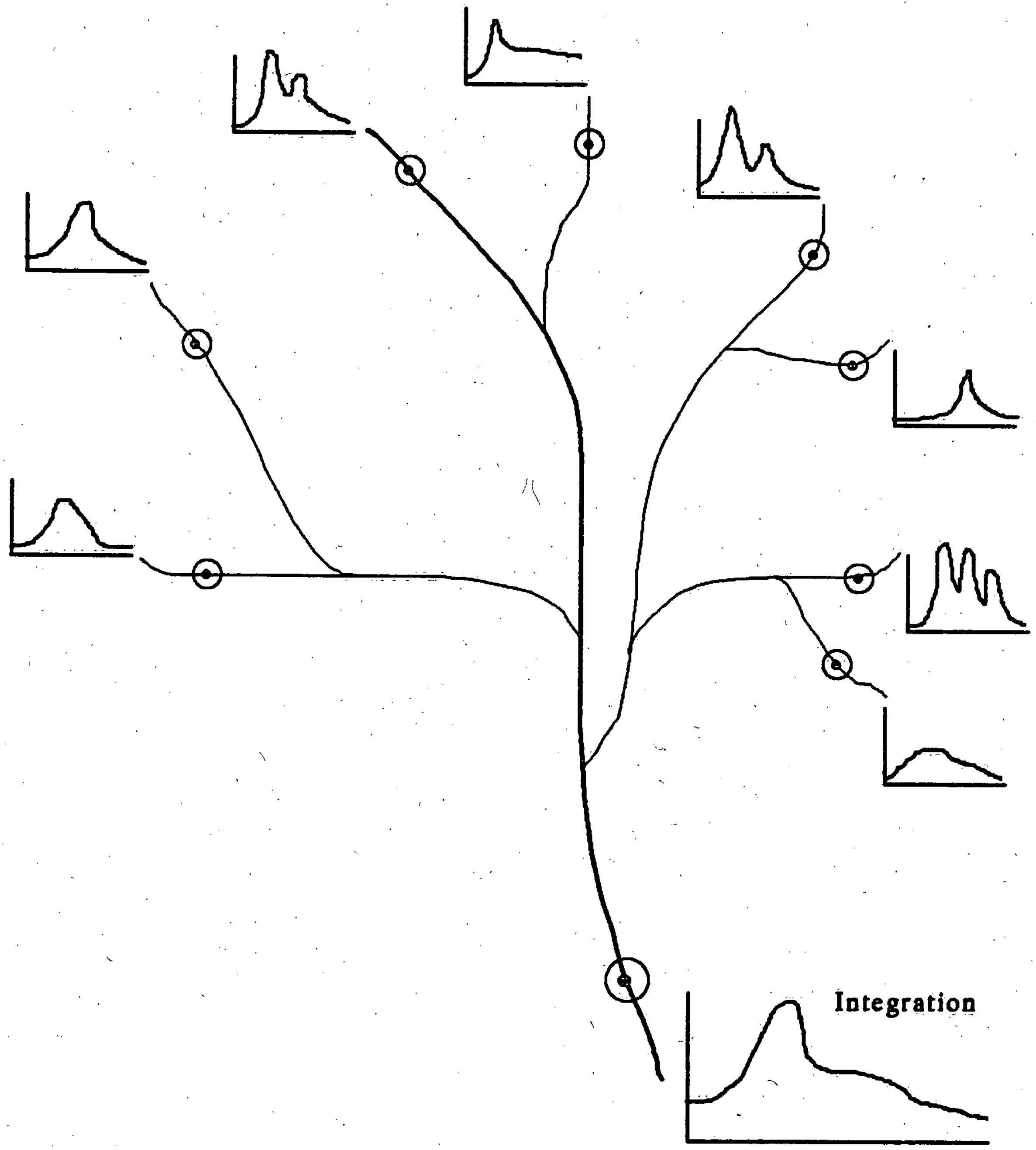
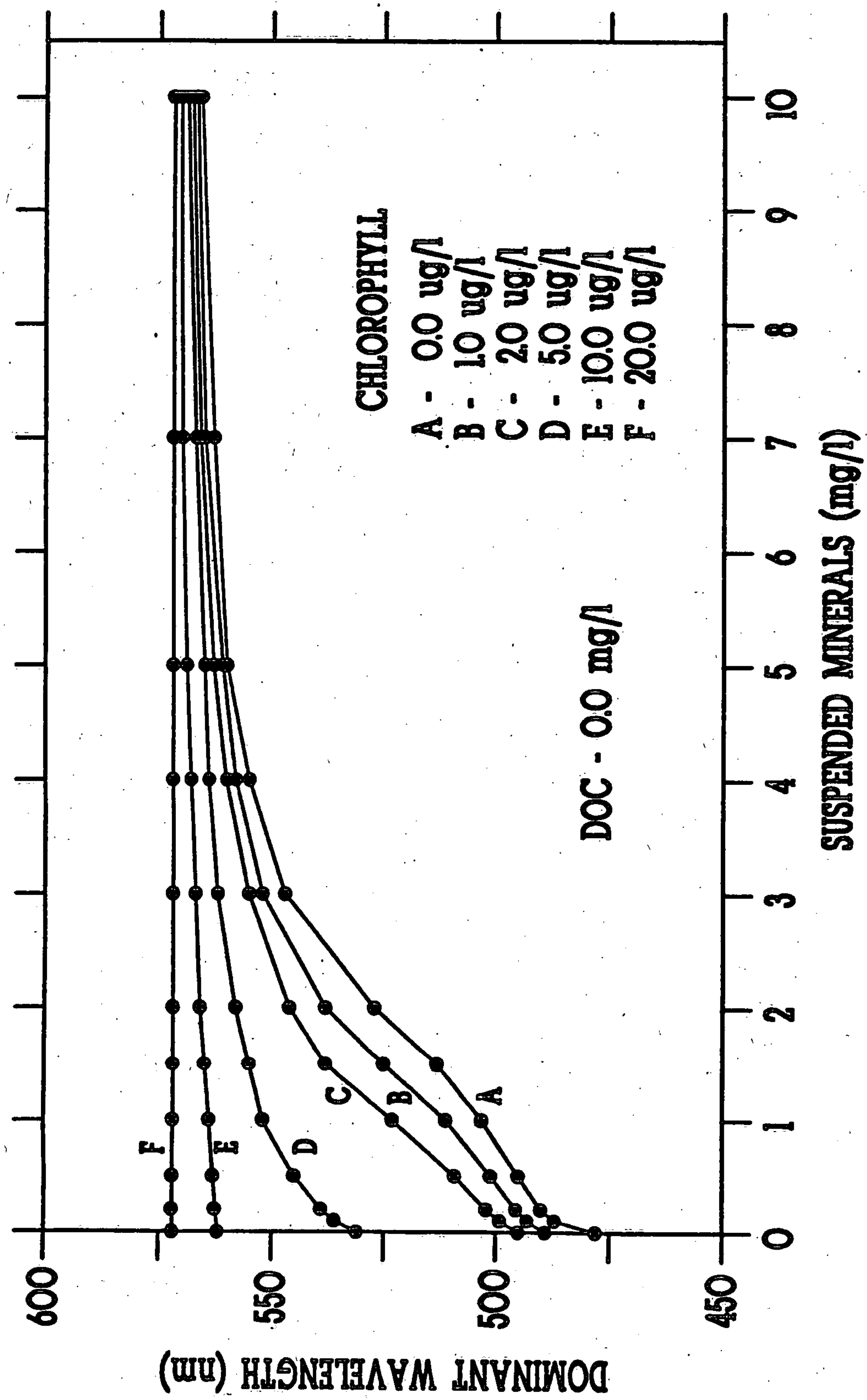
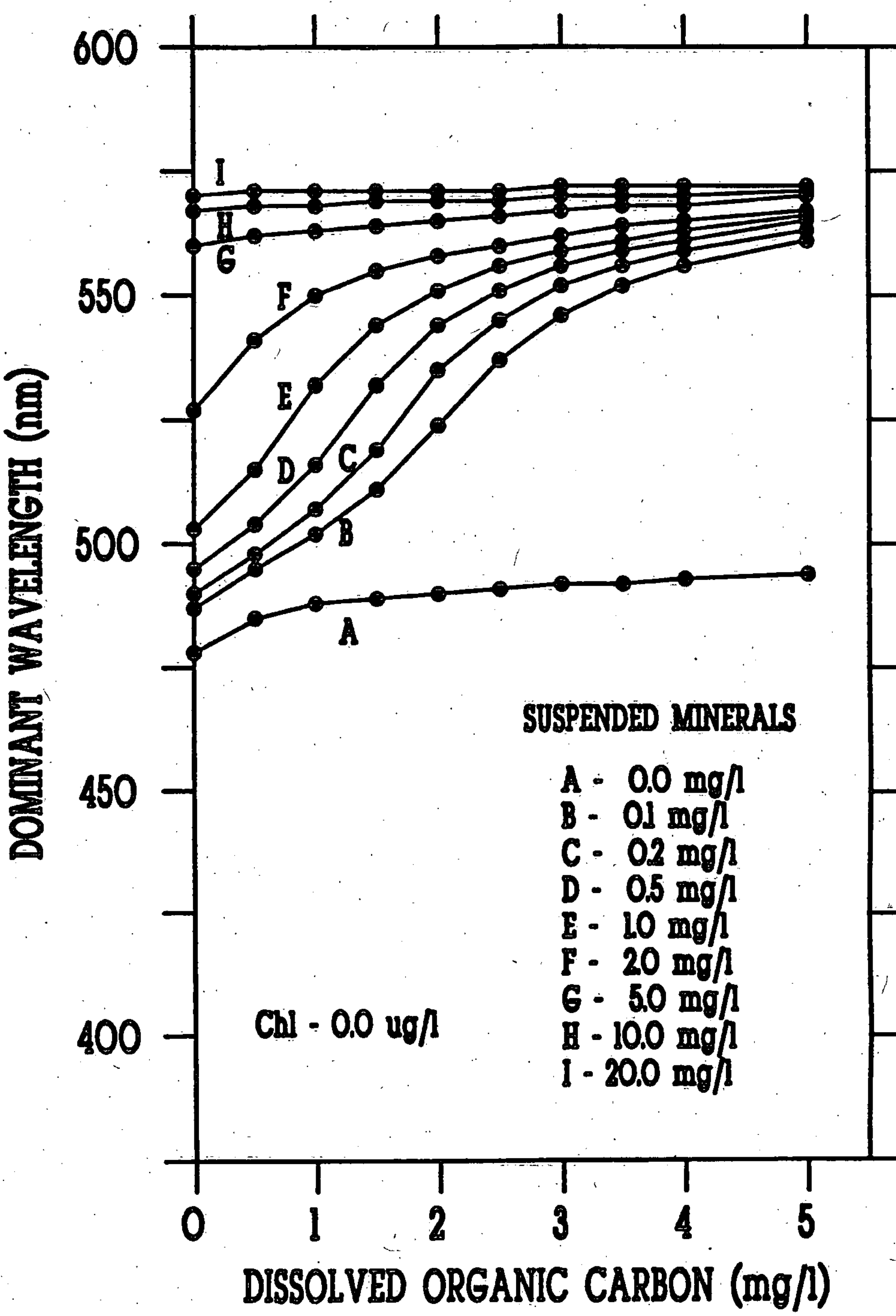


FIGURE 11



DOMINANT WAVELENGTH (nm)
600
550
500
450
SUSPENDED MINERALS (mg/l)
0
1
2
3
4
5
6
7
8
9
10
DOC - 0.0 mg/l
CHLOROPHYLL
A - 0.0 ug/l
B - 1.0 ug/l
C - 2.0 ug/l
D - 5.0 ug/l
E - 10.0 ug/l
F - 20.0 ug/l
A
B
C
D
E
F

FIGURE 12



DOMINANT WAVELENGTH (nm)
600
550
500
450
400
0
1
2
3
4
5
DISSOLVED ORGANIC CARBON (mg/l)
I
H
G
F
E
D
C
B
A
SUSPENDED MINERALS
A - 0.0 mg/l
B - 0.1 mg/l
C - 0.2 mg/l
D - 0.5 mg/l
E - 1.0 mg/l
F - 2.0 mg/l
G - 5.0 mg/l
H - 10.0 mg/l
I - 20.0 mg/l
Chl - 0.0 ug/l

FIGURE 13

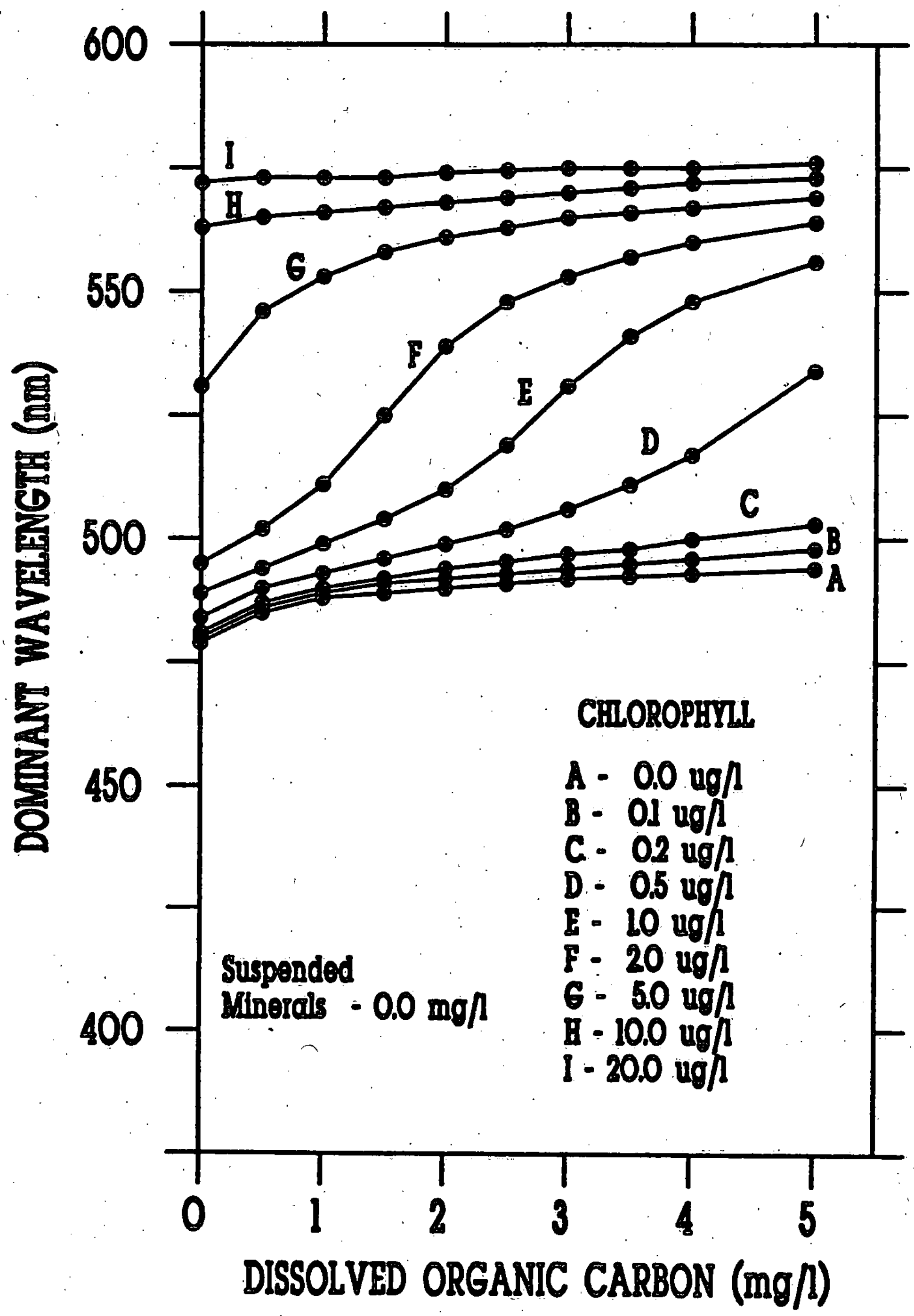

600
550
500
450
400
DOMINANT WAVELENGTH (nm)
0
1
2
3
4
5
DISSOLVED ORGANIC CARBON (mg/l)
I
H
G
F
E
D
C
B
A
CHLOROPHYLL
A - 0.0 ug/l
B - 0.1 ug/l
C - 0.2 ug/l
D - 0.5 ug/l
E - 1.0 ug/l
F - 2.0 ug/l
G - 5.0 ug/l
H - 10.0 ug/l
I - 20.0 ug/l
Suspended Minerals - 0.0 mg/l

FIGURE 14

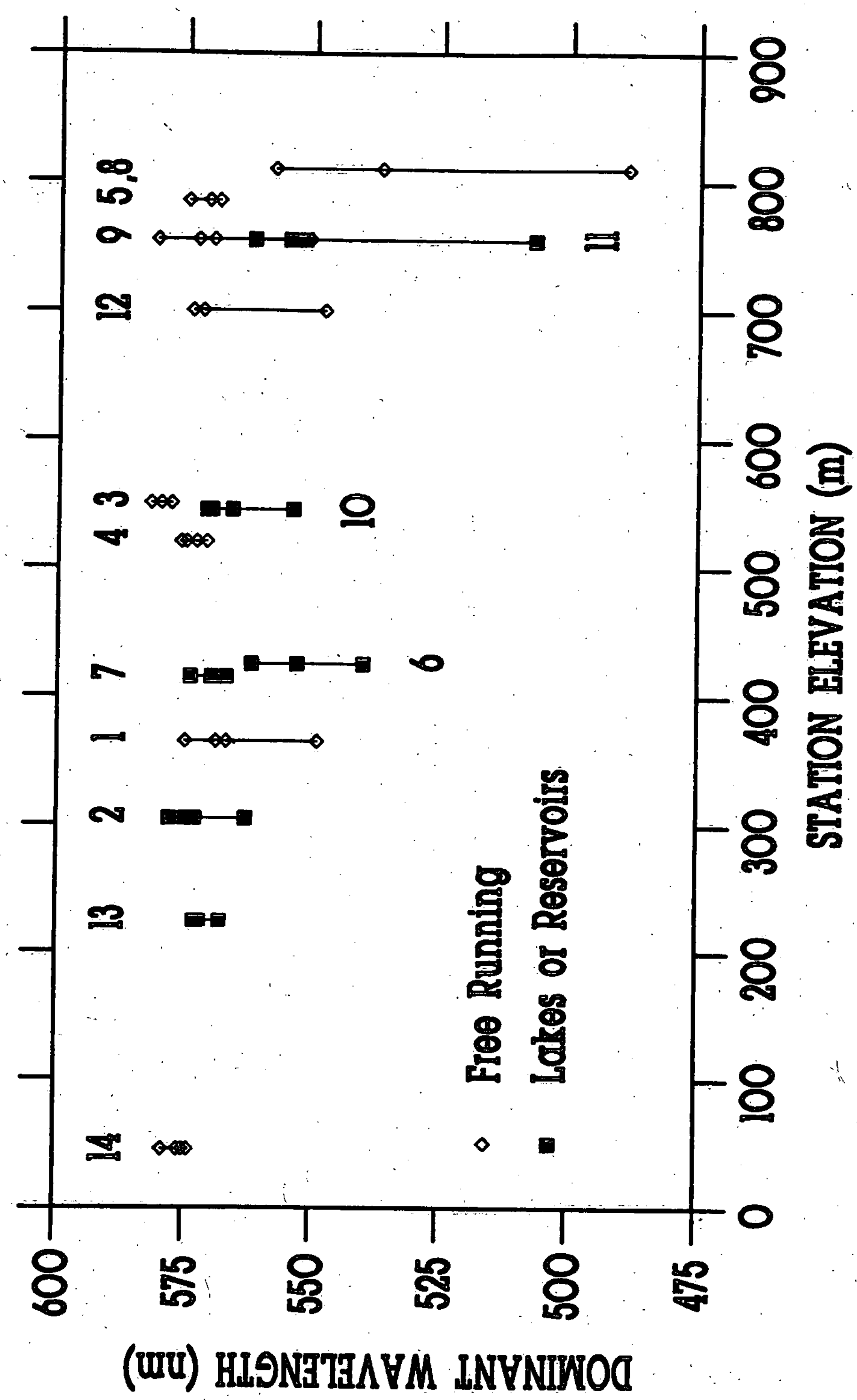

DOMINANT WAVELENGTH (nm)
600
575
550
525
500
475
STATION ELEVATION (m)
0
100
200
300
400
500
600
700
800
900
Free Running
Lakes or Reservoirs
14
13
2
1
7
6
4
3
10
12
9
11
5,8

FIGURE 15

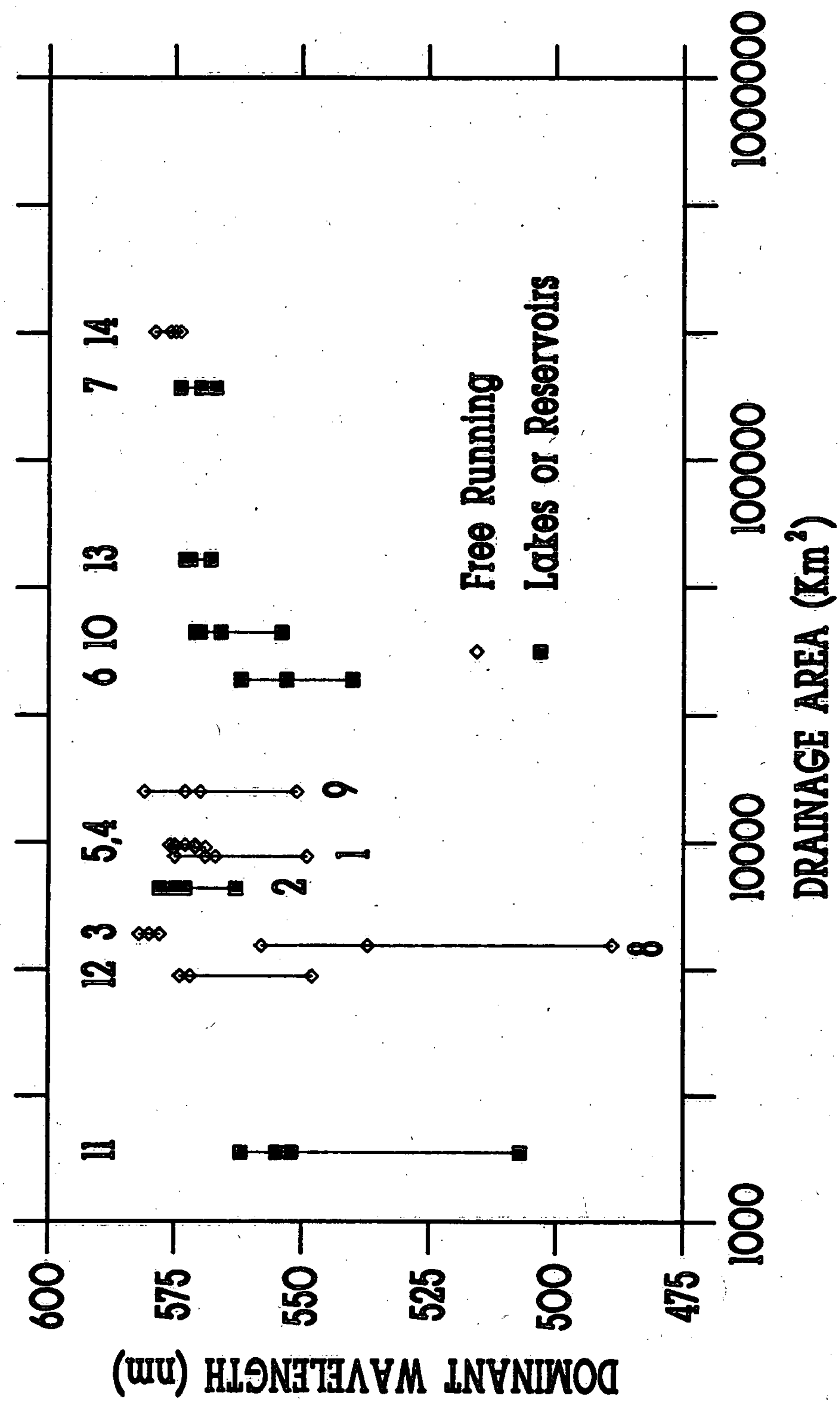

DOMINANT WAVELENGTH (nm)
600
575
550
525
500
475
DRAINAGE AREA (Km²)
1000
10000
100000
1000000
11
12
3
8
2
5,4
1
9
6
10
13
7
14
Free Running
Lakes or Reservoirs

FIGURE 16

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Environment Canada Environnement Canada

Canada

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C.P. 5050, BURLINGTON (ONTARIO) L7R 4A6

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