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RELATIONSHIPS AMONG SECCHI DISK DEPTH, BEAM ATTENUATION COEFFICIENT, AND IRRADIANCE ATTENUATION COEFFICIENT FOR GREAT LAKES WATERS

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ABSTRACT

Optical data collected between 1973 and 1979 are utilized to discuss the relationships among the directly observed Secchi disk depths and the directly measured total attenuation coefficients and irradiance attenuation coefficients in Lakes Erie, Ontario, Superior and Huron, as well as Georgian Bay. Tables and curves are presented depicting these mathematical relationships obtained by statistical regressions. These relationships are used to effect an intercomparison of the four Laurentian Great Lakes. In addition, subsurface, vertically downward sighting ranges are estimated and compared to the Secchi disk depths as determined from the mathematical regressions.

RÉSUMÉ

On utilise les données optiques recueillies entre 1973 et 1979 pour examiner les relations entre les observations directes des profondeurs de disparition du disque de Secchi et la mesure directe des coefficients d'atténuation totale et des coefficients d'atténuation de l'éclairement énergétique dans les lacs Erié, Ontario, Supérieur et Huron ainsi que dans la Baie Georgienne. Les relations mathématiques sont présentées sour forme de tableaux et de courbes obtenus par régressions statistiques. Ces relations sont utilisées pour exécuter une intercomparaison entre les quatre Grands Lacs laurentiens. En outre, on évalue les portées de visées verticales vers le bas sous la surface et on les compare aux profondeurs de disparition du disque de Secchi, obtenues grâce aux régressions mathématiques.

MANAGEMENT PERSPECTIVE

Secchi disks have long been used as simple and convenient devices to obtain instant physiological estimates of near-surface natural water clarity. The concept of visually tracking a controlled sinking object until it disappears from view, first seriously proposed by Angelo Secchi in 1866, is still in widespread current use. Aquatic biologists, chemists and physicists value Secchi depth records as an informal visual index of suspended sediment and biomass transport, plant life growth and decay, trophic status, and seasonal variations in aquatic clarity, a direct consequence of the fact that the depth at which a Secchi disk disappears from view is inversely proportional to the amount of suspended and dissolved organic and inorganic material residing in the water column.

Although a highly subjective parameter, the Secchi disk depths have been shown to be mathematically related to the optical property (c+k) which is the sum of two attenuation coefficients, one associated with a collimated beam distribution (c is defined as the total or beam attenuation coefficient) and one associated with an uncollimated diffuse distribution (k is defined as the irradiance attenuation coefficient). Submerged optical instruments such as the transmissometer can reliably yield _in situ_ measurements of c and the spectroradiometer can reliably yield _in situ_ determinations of k. NWRI/CCIW has, as part of its lake-by-lake surveillance and research plan, obtained such Secchi disk and optical instrumentation data routinely since 1973. The large volume of data thus collected has enabled statistically significant regressions to be performed among the optical data sets, and the resulting relationships among the Secchi disk depth, beam attenuation coefficient, and irradiance attenuation coefficient are presented in this communication for four of the Laurentian Great Lakes (no data were obtained by NWRI on Lake Michigan).

It is fully recognized that extreme caution must be exercised when applying and interpreting regressions obtained among subjective physiological Secchi disk depth values and scientifically objective c and k determinations. However, it is also fully recognized that Secchi disk depth determinations, because of their convenience, inexpensive operational costs, and deceptive simplicity, are a realistic fact-of-life. Consequently, when used carefully and properly, such statistical correlations can be used to assist in the evaluation of Secchi disk records. These correlations also provide a valuable basis for the intercomparison of the optical properties of the Great Lakes, and such an intercomparison is discussed in this communication. To further this intercomparison and illustrate a high degree of interconsistency among the optical data sets collected by NWRI, a discussion of yet another subjective physiological concept is presented.

This subjective concept is the subsurface sighting range, and such subsurface sighting ranges are estimated for each of the four Great Lakes (plus Georgian Bay) on the assumption that a) the observer is just beneath the air/water surface and looking vertically downwards, b) the object being sighted is of the size and reflectivity of a Secchi disk, and c) the reflectivity of the background water can be expressed as its volume reflectance (also a directly measured optical parameter). Such estimated subsurface sighting ranges compare quite well with Secchi disk depth values resulting from the use of the statistical regression equations.

PERSPECTIVE - GESTION

On utilise depuis longtemps le disque de Secchi, appareil simple et pratique, pour obtenir une évaluation instantanée physiologique de la clarté naturelle de l'eau près de la surface. Le procédé, qui consiste à suivre visuellement un objet qui coule sous contrôle, jusqu'à ce qu'il disparaisse, a été proposé pour la première fois de façon rationnelle par Angelo Secchi en 1866 et il est encore largement utilisé de nos jours. Les biologistes, les chimistes et les physiciens du milieu aquatique considèrent les relevés de profondeurs Secchi comme un indice visuel non formel du transport des sédiments et de la biomasse en suspension, de la croissance et de la décomposition végétales, de l'état de la chaîne trophique et des variations saisonnières de la clarté aquatique. Ceci est une conséquence directe du fait que la profondeur à laquelle disparaît le disque de Secchi est inversement proportionnelle à la quantité des matières organiques et inorganiques, dissoutes et en suspension, présentes dans la colonne d'eau.

On a montré que la profondeur de disparition du disque de Secchi, malgré son caractère fortement subjectif, présente une relation mathématique avec la propriété optique (c+k) qui est la somme de deux coefficients d'atténuation, l'un associé à la distribution d'un faisceau collimaté (c est le coefficient d'atténuation totale) et l'autre associé à la distribution diffuse non collimatée (k est le coefficient d'atténuation de l'éclairement énergétique). Grâce à des instruments optiques submergés, on peut effectuer des mesures fiables sur place des deux coefficients : le transmissomètre dans le cas de c et le spectroradiomètre dans celui de k. L'INRE/CCEI effectue de façon régulière depuis 1973 des mesures au disque de Secchi et aux instruments optiques, dans le cadre de son plan de surveillance et de recherche appliqué à chaque lac. Le grand volume des données ainsi recueillies a permis d'exécuter des régressions statistiquement significatives parmi les ensembles des données optiques et l'on présente dans ce document les relations calculées entre les valeurs obtenues par le disque de Secchi et les valeurs du coefficient d'atténuation totale et du coefficient d'atténuation de l'éclairement énergétique, et ce, pour quatre des Grands Lacs laurentiens puisque l'INRE ne dispose pas de données pour le lac Michigan.

Nous sommes tout à fait conscients de l'extrême prudence dont il faut faire preuve lorsque l'on applique et l'on interprète des régressions obtenues à partir de valeurs physiologiques subjectives comme les profondeurs de disparition du disque de Secchi et de valeurs objectives du point de vue scientifique comme les coefficients c et k. Nous sommes toutefois tenus de reconnaître que les mesures effectuées grâce au disque de Secchi, en raison de leur caractère pratique, du faible coût d'exploitation et de la simplicité trompeuse, constituent une réalité courante. Par conséquent, de telles corrélations statistiques utilisées à bon escient peuvent permettre d'évaluer les relevés des profondeurs de disparition du disque Secchi. En outre, ces corrélations nous permettent aussi d'effectuer une comparaison des propriétés optiques des Grands Lacs, ce que nous examinons dans le document. On présente également dans ce document l'examen d'un autre concept physiologique subjectif pour compléter cette comparaison et illustrer le degré élevé d'uniformité parmi les ensembles de données optiques relevées par l'INRE.

Ce concept subjectif est la portée de visée sous la surface. Nous évaluons les portées de visées sous la surface pour chacun des quatre Grands Lacs (ainsi que pour la Baie Georgienne) en nous basant sur l'hypothèse que

a) la visée verticale vers le bas se fait à partir d'un point situé juste au-dessous de la surface, que b) l'objet visé est de la taille et de la réflectivité d'un disque Secchi et que c) la réflectivité de l'eau de fond peut être exprimée par sa réflectance volumique (également un paramètre optique mesuré directement). Ces portées de visées sous la surface ainsi évaluées soutiennent bien la comparaison avec les valeurs de la profondeur de disparition du disque de Secchi obtenues par l'utilisation des équations de régression statistiques.

INTRODUCTION

Historically, estimates of natural water clarity have evolved from those resulting from the use of Secchi disks to those resulting from the use of submerged optical sensing devices. Two such commonly utilized optical devices are the transmissometer and the spectroradiometer. Despite the very apparent conflict between the highly subjective nature of the Secchi disk methodology and the considerably less subjective nature of the methodologies pertinent to the *in situ* optical instrumentation, the convenience, deceptive simplicity, and the longevity of the existing data base associated with Secchi disk usage have resulted in the Secchi disk's having become an integral component of large lake surveillance strategies. In many instances, Secchi disk depth observations form the only major "optical history" for water bodies on a global scale.

The concept of lowering an object (something white or distinctive enough to facilitate its ready recognition by the human eye) into deep waters and visually tracking that object until it disappears from view (Secchi, 1866; Duntley and Preisendorfer, 1952) is an attractive method of obtaining an instant evaluation of aquatic clarity. Further, this simple and subjective data gathering procedure may, through appropriate physical and physiological considerations, be converted into quantitative expressions for the depth rate of decay of natural light in natural water masses (Preisendorfer, 1953; 1976; 1986; Hϕjerslev, 1986; Gordon and Wouters, 1978; and others). The

Secchi disk depth (the depth at which the disk disappears from the surface observer's view), expressed in metres, may be used to determine a quantitative estimate of the apparent optical property (c+k), expressed in metres^{-1}, where

c = total (or beam) attenuation coefficient, the fraction of radiant energy removed from a collimated beam per unit distance at a particular depth Z resulting from the combined processes of absorption and scattering.

k = irradiance attenuation coefficient, the logarithmic depth derivative of the downwelling irradiance at a particular depth Z.

Thus, the use of Secchi disks results in the estimation of an optical property which is in part attributable to a beam (i.e. collimated radiant flux) distribution and in part attributable to an irradiance (i.e. uncollimated radiant flux) distribution.

Beam transmissometry is the measurement of the propagation of a beam of light through a given medium over a known path length. Consequently, by directly measuring the optical transmission, a transmissometer may be used to provide a reliable estimate of c. By profiling the transmissiometer, the beam attenuation coefficient may be obtained as a function of depth Z.

In situ spectral irradiance profiles are readily obtained by directly submerging irradiance meters such as scanning spectroradiometers. These profiles yield reliable estimates of not only the downwelling irradiance attenuation coefficient k(Z), but also of the subsurface irradiance reflectance ratio (volume reflectance), R(Z), which is defined as the ratio of the upwelling to downwelling irradiance at a depth Z.

The National Water Research Institute has, as part of its lake optics program, collected Secchi disk, transmission, and spectral irradiance data since 1973 in four of the Laurentian Great Lakes (no direct measurements were performed in Lake Michigan). These direct optical measurements were performed as part of the NWRI/CCIW Surveillance Program and utilized Martek XMS transmissometer systems and Techtum QSM Quanta Spectrometers. The purpose of this communication is two-fold:

a) To relate, through statistical regressions, Secchi disk depth values S to each of the optical parameters c (total attenuation coefficient) and k (irradiance attenuation coefficient).

b) To use these relationships to illustrate an optical intercomparison of Lakes Superior, Huron, Erie, and Ontario.

BEAM ATTENUATION COEFFICIENT AND SECCHI DISK DEPTH

Since the optical measurements were performed as part of the Great Lakes Surveillance Program, such data were obtained in a spatial and temporal manner conforming to the priorities and responsibilities of the surveillance mission. Consequently, the optical data considered in this communication include Lake Superior data of 1973, Lake Huron/Georgian Bay data of 1974, Lake Erie data of 1975, and Lake Ontario data collected from 1974 to 1979.

Using the MARTEK XMS transmissometers of 1 m or 0.25 m path lengths, a FOV of 2.3°, and a Wratten 45 optical filter, (centred at 485 nanometres), the total attenuation coefficient c (in m^{-1}) was determined for each surveillance station from

$$c(Z) = \frac{1}{X} \ln \left(\frac{100}{T(Z)}\right) \qquad (1)$$

where T = transmission in %

X = path length in metres

Z = depth

For the purpose of comparison c(Z) values used in this work refer to a Z value of 1 metre on the tacit assumption that a well-mixed epilimnion over the normally encountered Secchi disk depths will not be inappropriately defined by the c(Z) at this depth.

Power law regressions between the inverse Secchi disk depth S^{-1} and the total attenuation coefficient were performed for each of the four lakes monitored. Table 1 lists the mathematical relationships resulting from these regressions, along with the correlation coefficients r, the number of (c, S^{-1}) data pairs entering into each regression, and the range of Secchi disk depth values encountered in each lake survey. Figure 1 illustrates an intercomparison of the regressions between c and S^{-1} for each of the lakes. Since the number of data pairs for each lake/lake region varied from 171 to 1442, only the calculated regression curves are shown in Figure 1. The scatter of the individual members of the data pair complement is not illustrated. Significant individual scatter, however, does occur, but, as seen from the correlation coefficients listed in Table 1, the existing individual statistical scatter is overcome by the sheer volume of collected data pairs. It is evident that, in progressing from Lake Superior to Georgian Bay to Lake Ontario to Lake Huron to Lake Erie, a higher ratio of c to S^{-1} is generally encountered.

IRRADIANCE ATTENUATION COEFFICIENT

The total radiation in the 400-700 nm wavelength interval is defined as the photosynthetic available radiation (PAR) and is expressed in units of quanta irradiance (μ einsteins/m²/sec). For each of the Great Lakes studied, irradiance attenuation coefficient values, k_{PAR}, were determined in the manner previously described by Jerome et al. (1983). Directly measured quanta irradiance profiles were obtained for the wavelength band 400 to 700 nm. The profiles were considered from the surface to depths between the 10% and 1% irradiance levels, since, as shown by Kirk (1977), the profile of PAR does not follow a simple exponential form throughout the entire water column. The irradiance attenuation coefficients for PAR, k_{PAR}, were determined by a least squares fit to each quanta irradiance profile.

Linear regressions were then performed for appropriate (c, k_{PAR}) data pairs, and the results of these regressions are summarized in Table 2. The path lengths and FOV appropriate for all the transmissometer data used to calculate c are 0.25 m or 1 m and 2.3°, respectively. Figure 2 illustrates an intercomparison of these regressions between c and k_{PAR} for the general range of values of these parameters observable in each lake or lake region.

Since the irradiance attenuation coefficient for PAR, k_{PAR}, may be mathematically expressed as a function of the total attenuation coefficient c (Table 2), and c may be mathematically expressed as a function of the inverse Secchi disk depth S^{-1} (Table 1), then k_{PAR} may be expressed as a function of S^{-1}. These mathematical relationships between k_{PAR} and S^{-1} would reflect the power law relationship that exists between c and S^{-1}. However, for each lake region with the exception of Lake Ontario, the range of S^{-1} values in the (k, S^{-1}) data pairs is included within the nearly linear portion of the (c, S^{-1}) curve. Therefore, these ranges of the regression data sets which yielded Table 1 were curve-fitted to straight lines. Two straight line segments were required for Lake Ontario. The linear relationships thus obtained were combined with the equations of Table 2 to provide the relationships between k_{PAR} and S^{-1} in linear representations. These linear relationships between k_{PAR} and S^{-1} for each lake/lake region are listed in Table 3 along with the range of Secchi disk depth values for which the linearity approximation will apply. These ranges of Secchi disk depths, however, generally encompass the range of values normally observed in the offshore waters.

Figure 3 illustrates these linear relationships between k_{PAR} and S^{-1} for each lake/lake region monitored. It is readily seen that Lakes Huron, Superior, and Ontario and Georgian Bay display distinctly similar (k_{PAR}, S^{-1}) regressions, while Lake Erie displays a markedly different regression with a slope which is 50% higher than the slopes observed for the other water bodies. Figure 4 illustrates the (k_{PAR}, S^{-1}) regressions over the common range of Secchi disk depth values $S \geq 2$ m, while Figure 5 illustrates the effect of averaging the regressions of Lakes Huron, Superior, and Ontario and Georgian Bay into a single relationship over the range $2 \text{ m} \leq S \leq 10$ m. Consequently, with the exclusion of Lake Erie, the Great Lakes waters monitored by the NWRI surveillance program may be defined by the single relationship

$$k_{PAR} = 0.757\ S^{-1} + 0.07 \qquad (2)$$

over the range $2 \text{ m} \leq S \leq 10$ m. The average percent difference between the use of this single equation and the actual regressions as listed in Table 3 is 2% for Lake Huron, 5% for Lake Superior, 7% for Lake Ontario, and 5% for Georgian Bay.

SUBSURFACE SIGHTING RANGE

The subsurface sighting range is generally taken to represent the maximum distance at which an object may be detected underwater. Although the association of this parameter to a particular observer is highly subjective, the major governing factors to its numerical value are, obviously, the optical properties of the water. Large values of subsurface sighting range are associated with waters of high clarity, while small values of subsurface sighting range are associated with turbid waters. As discussed earlier, the two most obvious turbidity indicators from an optical standpoint are the total attenuation coefficient c and the irradiance attenuation coefficient k. The sum of these two attenuation coefficients (c+k) is frequently employed as an indicator of aquatic clarity, and it is this summed parametric property which is most readily related to both sighting range and Secchi disk depth. Consequently, if the sighting range considered is reckoned as being vertically downwards from the air/water interface, such a sighting range estimate could be reasonably considered to represent a zeroeth order approximation to the Secchi disk depth. It is certainly realized that such an intercomparison is being performed on non-identical physiological concepts. The sighting range is generally designed for divers and/or swimmers engaged in visual searches for objects whose presence may be anticipated, but whose precise whereabouts are unknown. Consequently, a sighting range is conceptualized for the physiological appearance of a foreign (to the ambient water mass) object into a field of view. The user of a Secchi disk, however, is fully aware of the presence of the disk and faithfully visually tracks its descent. Consequently, the Secchi disk depth is conceptualized for the physiological disappearance of a foreign object from a field of view. Nonetheless, a consideration of sighting ranges reckoned vertically downwards from the surface should, if considered properly, yield results which are not in direct conflict with the regressions presented thus far.

In addition to the aquatic medium influencing the subsurface sighting range associated with a submerged object, the properties of the submerged object itself strongly influence its ability to be visually detected (Preisendorfer, 1976; 1986; Duntley and Preisendorfer, 1952; Duntley et al., 1959; Duntley, 1960). In particular, the contrast of the object to its surroundings is of major importance. This contrast is dependent upon the reflectivity of the object, R_T, and the reflectivity of the background, R_B (this latter parameter is well approximated by either the bottom reflectance if the object is near lake bottom, or the volume reflectance of the water if the object is not near lake bottom).

The remaining factors of major influence to the subsurface sighting range associated with a submerged object are the physical size of the object, the direction of viewing, and the availability of subsurface light (this latter factor being directly related to the incident radiation).

As extensively discussed by Duntley (1960) and Preisendorfer (1976), nomographs may be constructed from which the sighting range may be obtained once the optical parameters k, c, R_T and R_B are known. Figure 6 illustrates such a nomograph. This particular nomograph considers physical objects of projected area $\geq$100 cm² viewed from the surface vertically downward for all lighting conditions between one hour subsequent to sunrise and one hour prior to sunset. To determine the subsurface sighting range, therefore, a direct measurement of the total attenuation coefficient c is first required. The corresponding value of the irradiance attenuation coefficient k may be calculated from the mathematical relationships of Table 2. Appropriate values of R_B must also be available. For near-surface sighting ranges, R_B may be represented by the subsurface volume reflectance, a precise value of which is obtained by direct spectro-radiometric measurements. In order to facilitate the use of the nomograph of Figure 6, a linear regression was performed between directly measured values of epilimnionic volume reflectance measurements and simultaneously measured values of c. Such regressions were not performed on a per-lake basis, but rather considered as a composite regression for all the lake data. Consequently, the regression was heavily weighted in favour of the lower Great Lakes, particularly Lake Ontario. Further, as has been extensively discussed in the literature (Gordon,1973; Gordon et al., 1975; Bukata et al., 1979; Jerlov, 1976; and many others), there is, at best, minimal scientific justification for regressing volume reflectance with total attenuation coefficient. These acknowledged criticisms of such regressions notwithstanding, however, the value of R_B, to a first approximation, was taken to be expressed by the regression

$$R_B = 0.015\,(c + 1.0) \qquad (3)$$

The reflectivity of the object, R_T, may be estimated as a number between 0 and 1 depending upon its colour and finish. Secchi disks are generally described by $R_T = 0.70$. Thus, the parameters (c+k) and $(R_T-R_B)/50R_B$ may be readily determined, and a straight line drawn between these values on Figure 6 yields the sighting range as its interception point with the nomograph curve. For smaller objects, non-vertical viewing directions, and differing conditions of incident radiation, other nomographs describing these situations would be required. Detailed information on the nature and applications of such nomographs may be found in Preisendorfer (1976).

Using the nomograph of Figure 6, the sighting ranges for an object ≥ 100 cm^2 area and characterized by an R_T of 0.70 (assuming a viewing direction vertically downwards from the air/water interface) were estimated for Lakes Ontario, Erie, Superior, and Huron, and for Georgian Bay. Figure 7 displays these calculated sighting ranges as a function of the transmission values T (percent transmission for a 1 metre path length) appropriate to the offshore near-surface waters of each of the Great Lakes during the summer months. As is evident from the figure, sighting ranges vary from as high as 20 metres in Lake Superior to as low as 1 or 2 metres in Lakes Erie and Ontario.

In an attempt to compare the near-surface vertical sighting ranges of Figure 7 with observed Secchi disk depths, equation (1) (relating T to c) and the equations listed in Table 1 (relating c to S^{-1} for each lake/lake region) were used to determine the relationships between Secchi disk depth S in metres and the percent transmission T for a 1 metre path length for each of the offshore near-surface lake/lake regions included within the NWRI summer surveillance corridors. These relationships are shown in Figure 8, with the accentuated segments of each curve corresponding to the transmission ranges depicted in Figure 7.

Despite the obvious differences between Figures 7 and 8, the equally obvious similarities between the two figures certainly suggests at least a zeroeth-order equivalence between the near-surface vertically-downwards sighting range and Secchi disk depth. Considering that (a) the above-water position of the Secchi disk user is at variance with the below-water position of the swimmer, (b) the nomograph of Figure 6 has been utilized on the basis of generalized methodologies independent of the variations among the Secchi disks employed, independent (in the case of R_B) of lake region considered, and also independent of the varying optical complexities governing the radiative transfer processes occurring within the water masses, and c) both Secchi disk depths and sighting ranges are very subjective physiological concepts, the distinct similarities between Figures 7 and 8 suggest a not unreasonable consistency existing among the regression relationships discussed in this communication.

CONCLUDING REMARKS

It must be clearly understood that this manuscript neither advocates nor condemns the extensive use of Secchi disk depths as a water clarity indicator. And while it certainly does advocate the continued (and extensive) use of submerged optical devices in surveillance and/or research-oriented activities, it must also clearly recognize the reality of the Secchi disk's popularity, a direct consequence of the continuing convenience and simplicity appropriately ascribed to it.

From Great Lakes surveillance data collected on four large lakes and spanning six field seasons, Secchi disk depth values have been statistically regressed with the optical parameters c (total attenuation coefficient) and k (irradiance attenuation coefficient). In addition a nomograph for estimating subsurface sighting range of an object at least 100 cm^2 in area being viewed by a swimmer just beneath the air/water interface and looking vertically downward was presented and used to determine such sighting ranges for the five Great Lakes/Great Lakes regions considered.

It was found that whereas the relationship between c and inverse Secchi disk depth S^{-1} varied from lake to lake, the relationships between k and S^{-1} displayed a remarkable similarity for each of the lakes exclusive of Lake Erie. The single relationship

$$k_{PAR} = 0.757\ S^{-1} + 0.07 \qquad (2)$$

adequately describes Lakes Huron, Superior, and Ontario, as well as Georgian Bay over the Secchi disk depth interval $2\ m \leq S \leq 10\ m$.

Perhaps the greatest hazard in relating, through statistical regression techniques, Secchi disk observations to direct optical measurements, lies in the tendency, once such relationships are established, to utilize Secchi disk readings to infer optical parameters which are much more appropriately obtained from other, more sophisticated measurement techniques. Such relationships tend to smooth out the effects of seasonal and spatial variations in the physical, chemical, and biological activity defining the lake system. These effects, along with the physiological subjectiveness of the Secchi disk user (in addition to the surface and atmospheric optical conditions which have been totally ignored in this communication) generate a very significant degree of statistical scatter among all pairs of optical data sets (particularly those data sets involving S). On a per-cruise basis, the limited number of data pairs further accentuates these statistical problems. These difficulties in generating local statistical regressions prohibits the unqualified recommendation that such Secchi disk relationships be utilized in future lake research and surveillance activities. However, the cautious and careful utilization of the Secchi disk relationships for the Great Lakes presented herein can be of both interest and consequence to the interpretation of existing historical data bases wherein Secchi disk depth determinations comprise the only available optical information.

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Table 1 **Relationships between total attenuation coefficient c and Secchi disk depth S for Great Lakes waters.**

Lake	Date	Path Length (m)	Range of Secchi Disk Depths (m)	Number of (c, S^{-1}) Data Pairs	Mathematical Relationship	Correlation Coefficient r
Superior	1973	1	$3 \leq S \leq 21$	291	$c=2.85(S^{-1})^{0.80}$	0.98
Huron	1974	1	$1.5 \leq S \leq 20$	184	$c=4.55(S^{-1})^{0.95}$	0.99
Georgian Bay	1974	1	$4 \leq S \leq 12$	171	$c=3.90(S^{-1})^{0.90}$	0.99
Erie	1975	0.25	$0.5 \leq S \leq 10$	347	$c=5.85(S^{-1})^{1.00}$	0.99
Ontario	1976-1979	0.25	$1 \leq S \leq 10$	1442	$c=4.35(S^{-1})^{0.90}$	0.99

Table 2 Relationships between total attenuation coefficient c and irradiance attenuation coefficient k_{PAR} for Great Lakes waters.

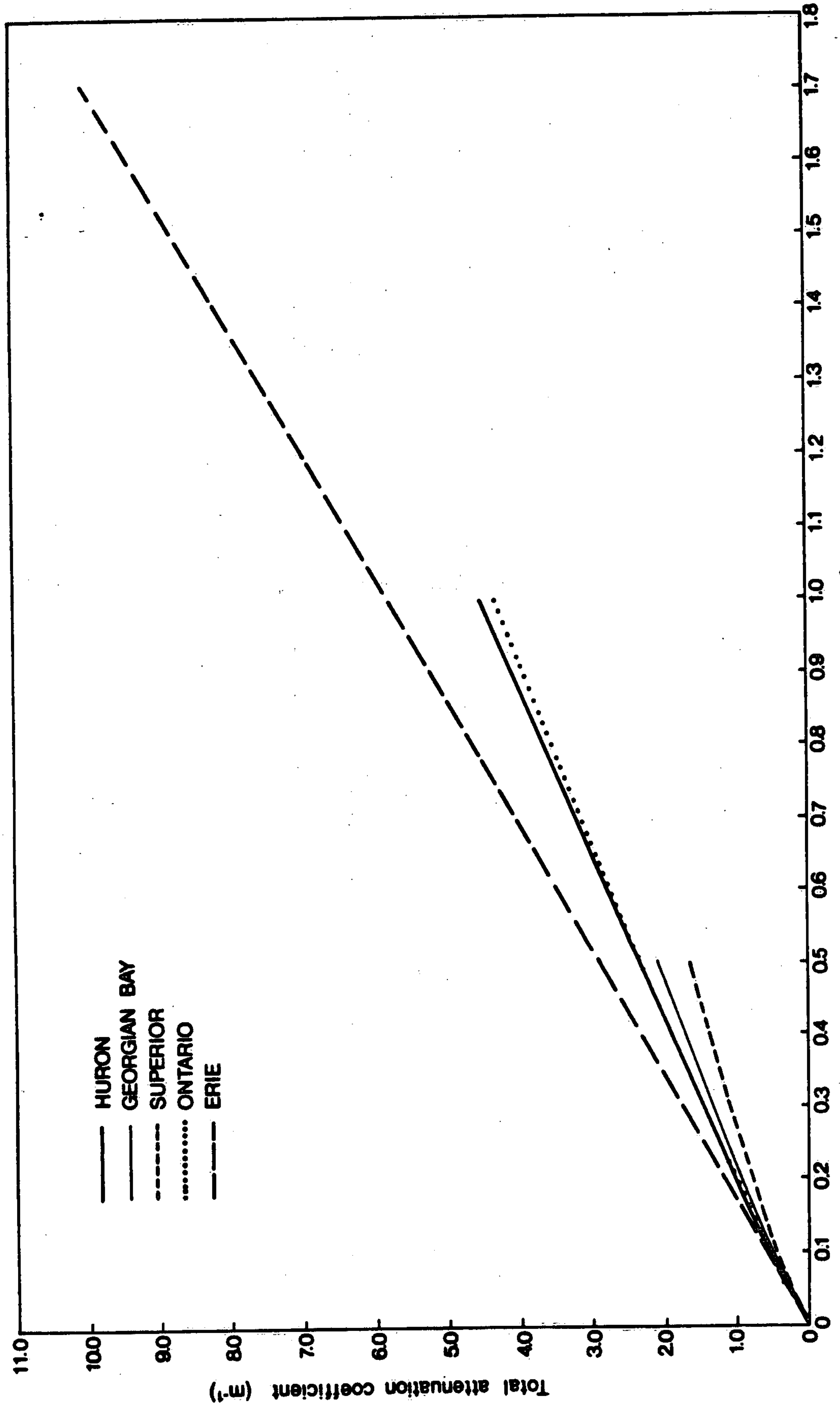
Lake	Date	Number of (c, k_{PAR}) Data Pairs	Mathematical Relationship	Correlation Coefficient r
Superior	1973	34	$k_{PAR}=0.195c+0.08$	0.86
Huron	1974	29	$k_{PAR}=0.160c+0.06$	0.83
Georgian Bay	1974	23	$k_{PAR}=0.185c+0.06$	0.73
Erie	1975	25	$k_{PAR}=0.220c+0.01$	0.98
Ontario	1975	22	$k_{PAR}=0.185c+0.02$	0.92

Table 3 **Linear relationships between the irradiance attenuation coefficient k_{PAR} and Secchi disk depth S for Great Lakes waters.**

Lake	Range of Secchi Disk Depths (m)	Mathematical Relationship
Superior	$2 \le S \le 20$	$k_{PAR}=0.67\ S^{-1}+0.10$
Huron	$1 \le S \le 20$	$k_{PAR}=0.74\ S^{-1}+0.07$
Georgian Bay	$2 \le S \le 20$	$k_{PAR}=0.81\ S^{-1}+0.07$
Erie	$0.5 \le 5 \le 10$	$k_{PAR}=1.28\ S^{-1}$
Ontario	$1 \le S \le 3$	$k_{PAR}=0.76\ S^{-1}+0.06$
Ontario	$3 \le S \le 10$	$k_{PAR}=0.86\ S^{-1}+0.03$

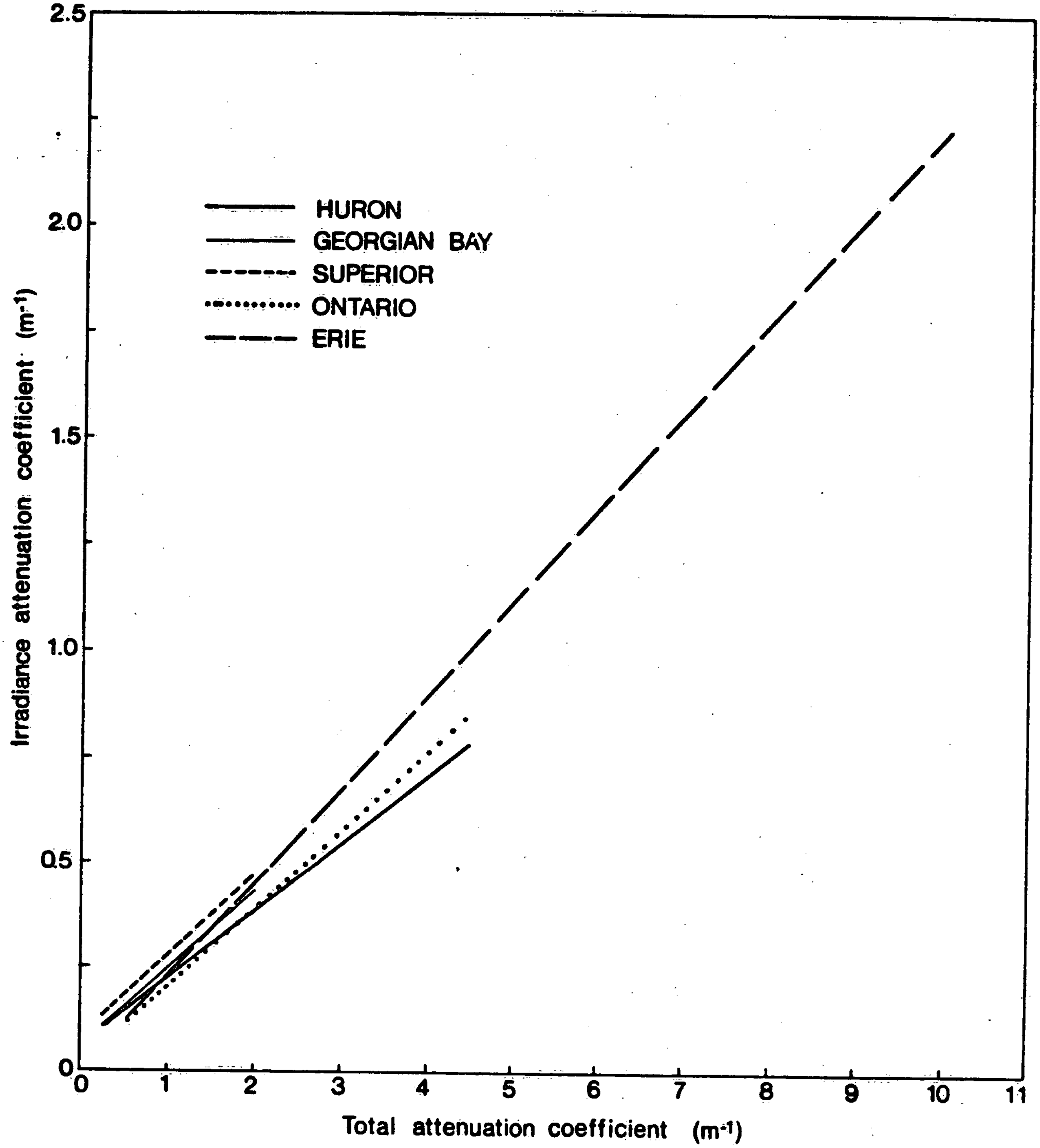
LIST OF FIGURES

Figure 8: Calculated relationships between Secchi disk depth values S and near-surface transmission T for Lake Superior, Lake Huron, Lake Ontario, Lake Erie, and Georgian Bay. The accentuated regions of each curve pertain to offshore, near-surface summer, optical transmission ranges.



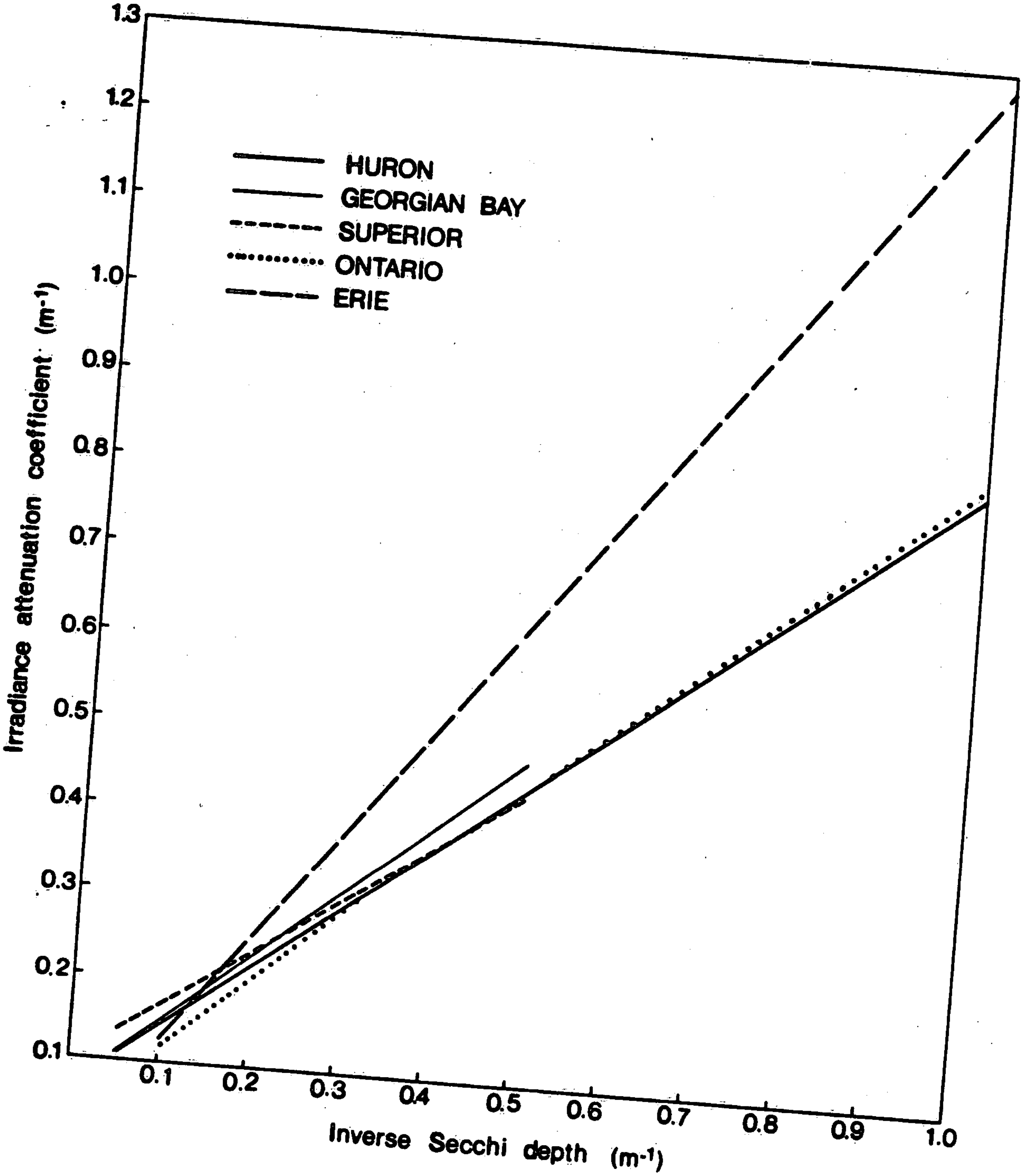
HURON
GEORGIAN BAY
SUPERIOR
ONTARIO
ERIE
Total attenuation coefficient (m⁻¹)
Inverse Secchi depth (m⁻¹)
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8

FIGURE 1



HURON
GEORGIAN BAY
SUPERIOR
ONTARIO
ERIE
Irradiance attenuation coefficient (m-1)
Total attenuation coefficient (m-1)
0
0.5
1.0
1.5
2.0
2.5
0
1
2
3
4
5
6
7
8
9
10
11

FIGURE 2



HURON
GEORGIAN BAY
SUPERIOR
ONTARIO
ERIE
Irradiance attenuation coefficient (m-1)
Inverse Secchi depth (m-1)
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

FIGURE 3

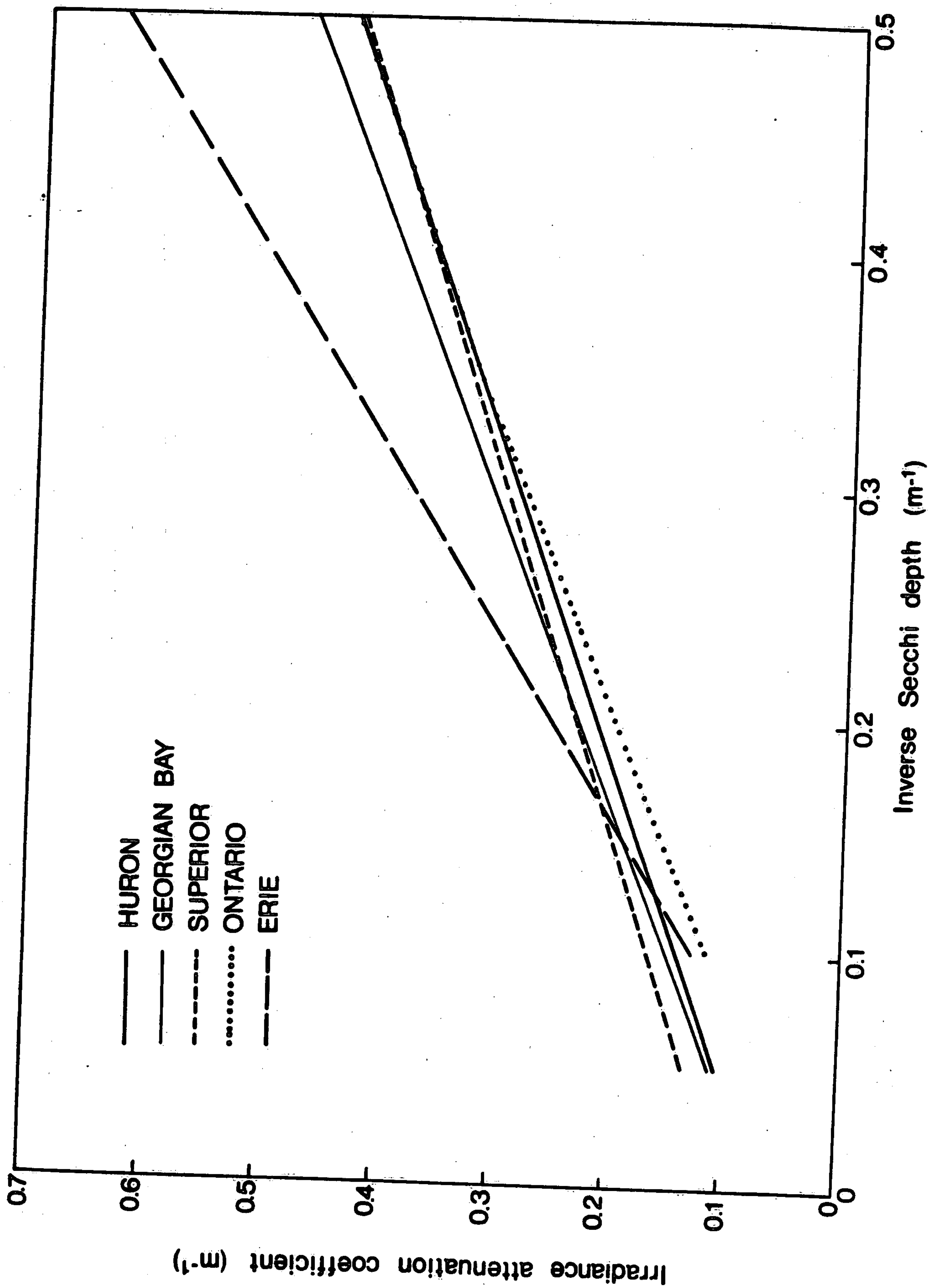

HURON
GEORGIAN BAY
SUPERIOR
ONTARIO
ERIE
Irradiance attenuation coefficient (m-1)
Inverse Secchi depth (m-1)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

FIGURE 4

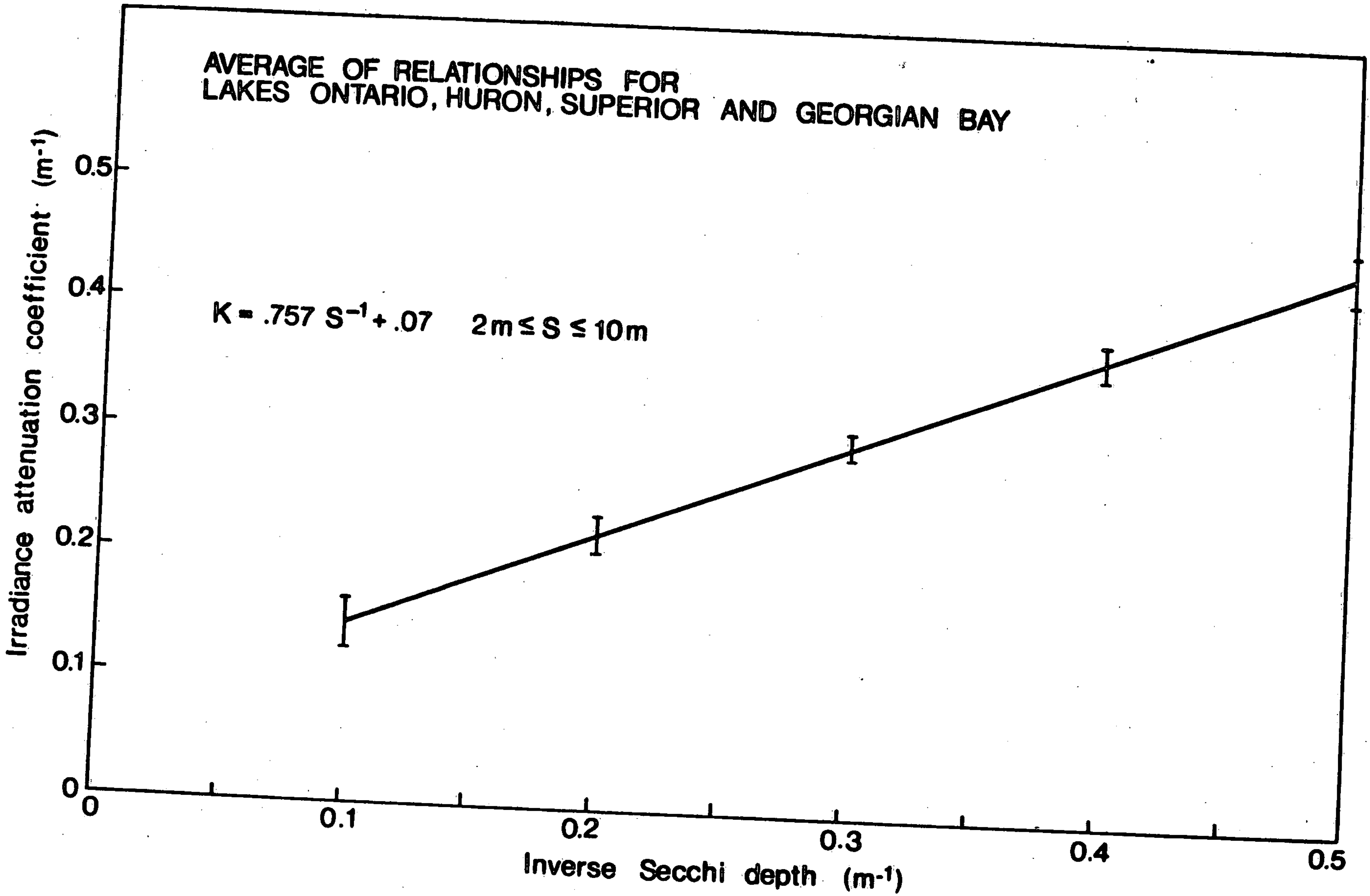
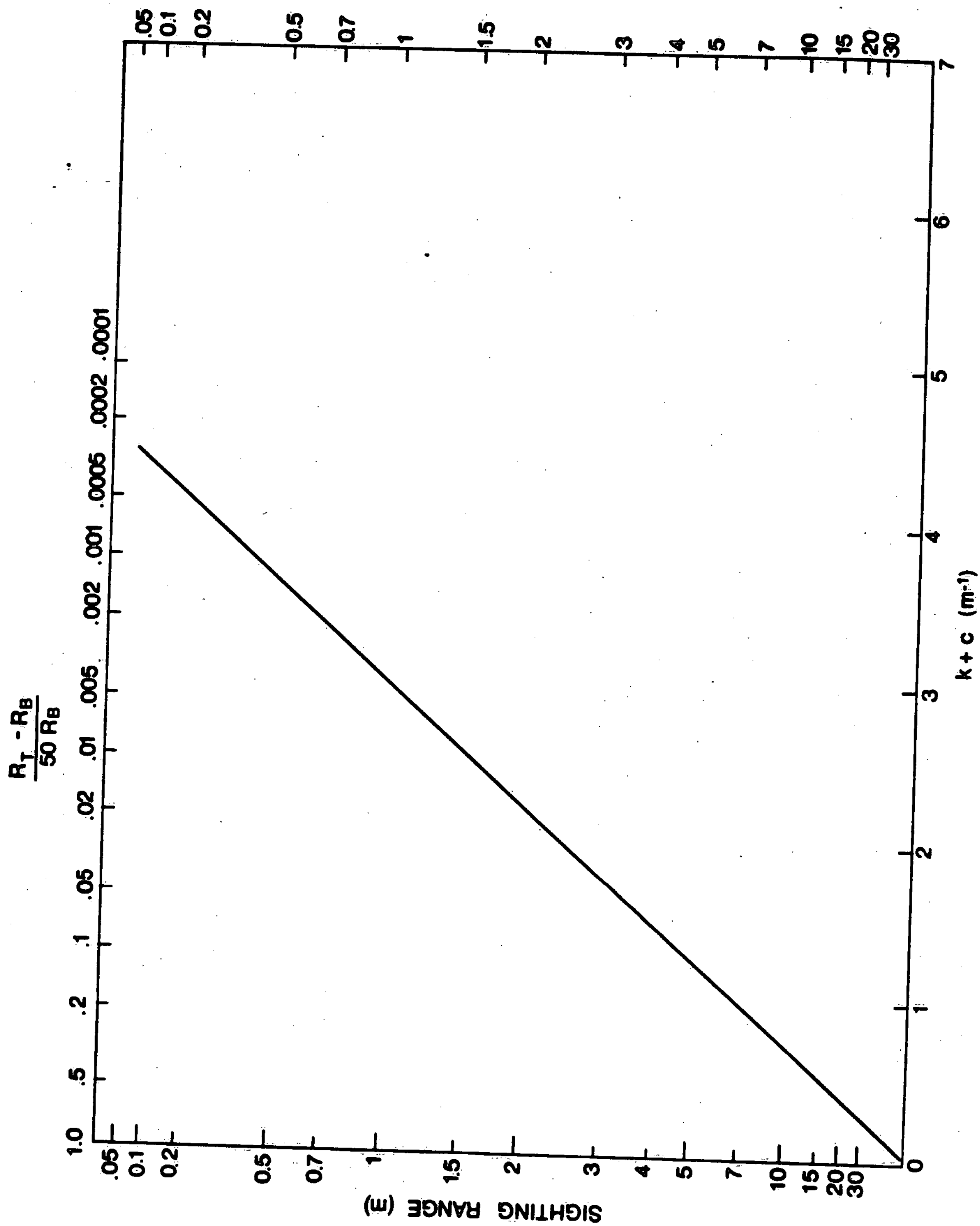
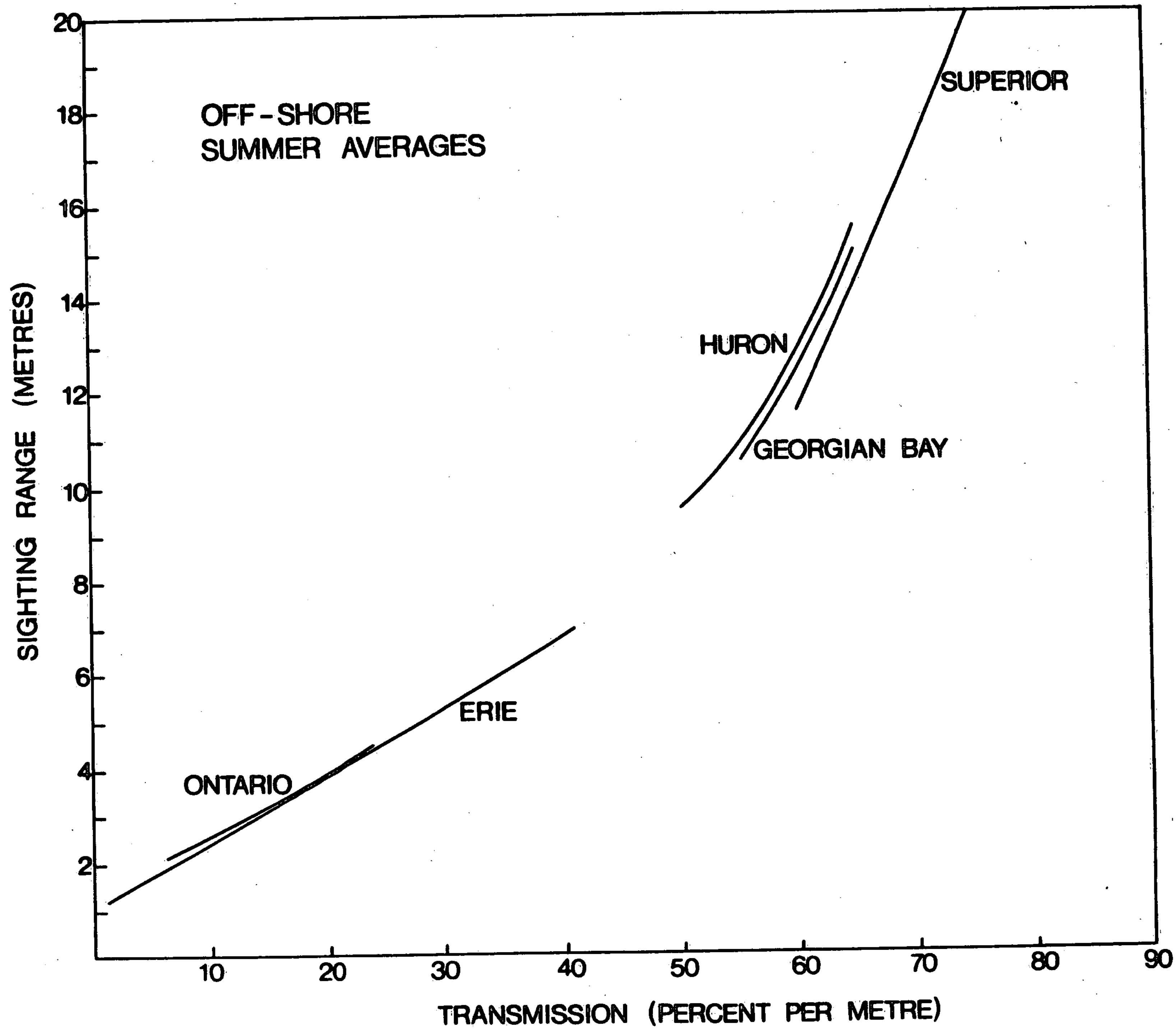

AVERAGE OF RELATIONSHIPS FOR
LAKES ONTARIO, HURON, SUPERIOR AND GEORGIAN BAY
K = .757 S⁻¹ + .07   2m ≤ S ≤ 10m
Irradiance attenuation coefficient (m⁻¹)
0
0.1
0.2
0.3
0.4
0.5
Inverse Secchi depth (m⁻¹)

FIGURE 5



$\frac{R_T - R_B}{50\,R_B}$
1.0
.5
.2
.1
.05
.02
.01
.005
.002
.001
.0005
.0002
.0001
SIGHTING RANGE (m)
.05
0.1
0.2
0.5
0.7
1
1.5
2
3
4
5
7
10
15
20
30
k + c (m⁻¹)
0
1
2
3
4
5
6
7

FIGURE 6



OFF-SHORE
SUMMER AVERAGES
SUPERIOR
HURON
GEORGIAN BAY
ERIE
ONTARIO
SIGHTING RANGE (METRES)
TRANSMISSION (PERCENT PER METRE)
20
18
16
14
12
10
8
6
4
2
10
20
30
40
50
60
70
80
90

FIGURE 7

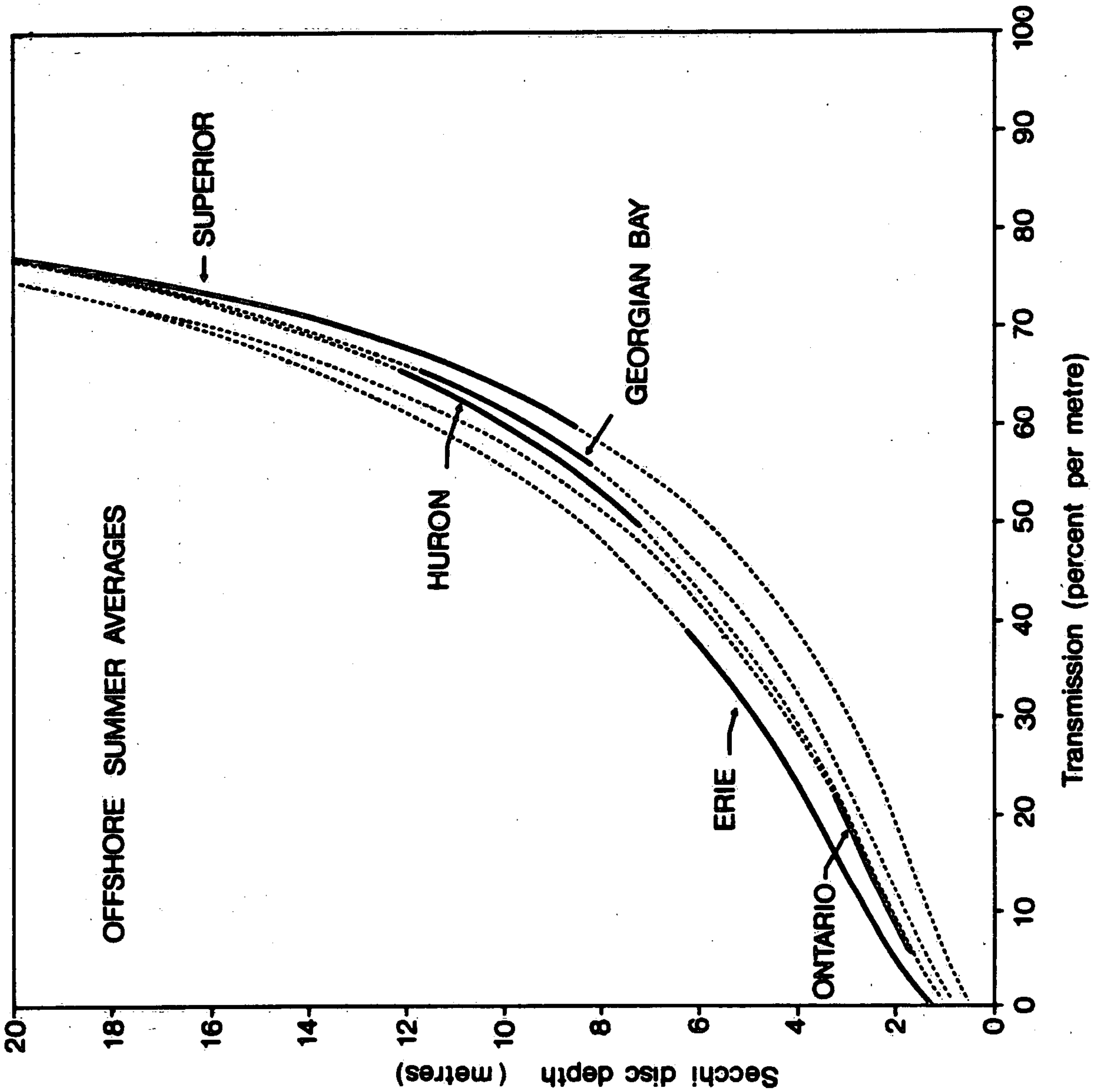

OFFSHORE SUMMER AVERAGES
SUPERIOR
GEORGIAN BAY
HURON
ERIE
ONTARIO
Secchi disc depth (metres)
0
2
4
6
8
10
12
14
16
18
20
Transmission (percent per metre)
0
10
20
30
40
50
60
70
80
90
100

FIGURE 8