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AN ESTIMATE OF THE

INFLUENCE OF SEDIMENT CONCENTRATION AND TYPE ON

REMOTE SENSING PENETRATION DEPTH FOR

VARIOUS COASTAL WATERS

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16. Abstract

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SUMMARY

Under the assumptions of collimated light, a homogenous water column, zero-molecular scattering, and constant ratio of volume-scattering function to scattering coefficient, estimates of the remote sensing depth parameter, Z_{90}, are made for various coastal waters at a wavelength of 540 nm. Calculations indicate that sediment concentration and type have a strong influence on remote sensing depth when concentrations are below 5 mg/ℓ. Above 5 mg/ℓ, the absorption of the sediments becomes large in comparison to that of water causing Z_{90} values to be less than 2 m with only small differences between various sediment types.

INTRODUCTION

LANDSAT experiments have demonstrated the feasibility of remote sensing for monitoring coastal waters. Studies are underway concerning the feasibility of advanced multispectral scanner systems for accurate monitoring of various water quality parameters. One item of interest in the analysis of data and the design of future instrument systems is the depth of penetration which influences the upwelling irradiance value at various wavelengths in the electromagnetic spectrum. Penetration depths influence band selection in multispectral scanner instruments and the selection of bands to be used in data analysis algorithms. Unfortunately, penetration depths for estuaries and continental shelf waters off the East and Gulf Coasts of the United States are not available. Because coastal waters contain a variety of sediments and dissolved substances, the depth of penetration for remote sensing is quite variable.

It is the purpose of this study to estimate relative water penetration depths for a variety of specific sites along the East and Gulf Coasts of the United States. Estimates will be made by applying experimental optical coefficients from reference 1 to nondimensional scattering model results given in reference 2. Remote sensing instrument sensitivity will not be considered. Estimates will be made by computing the depth above which 90 percent of the upwelling irradiance is originated (known as Z_{90}) for various water mixtures with different attenuation coefficients and absorption-to-scattering ratios. Where possible, light penetration depth will be compared with sediment concentration variation.

SYMBOLS

a	absorption coefficient for water-particle mixture, m^{-1}
a_{sed}	absorption coefficient for particles, m^{-1}
a_w	absorption coefficient for water (including dissolved substances), m^{-1}
s	scattering coefficient for water-particle mixture, m^{-1}
s_{sed}	scattering coefficient for particles, m^{-1}
α	attenuation coefficient for water-particle mixture, m^{-1}

Z_{90} depth of water-particle mixture from which 90 percent of the upwelling irradiance is originated, m

ANALYSIS OF PREVIOUS WORK

Reference 2 defined the effective penetration depth for remote sensing purposes as the layer thickness from which 90 percent of the total upwelling irradiance is originated. The depth of this layer is known as Z_{90}. While particular remote sensors may not see effects as deep as Z_{90}, and others may see deeper, this study will use Z_{90} as an approximate measure of the depth of penetration of interest for remote sensing. A homogenous water column from a scattering and absorption coefficient's viewpoint is also assumed. The relation of the upwelling Z_{90} to downwelling irradiance values will be discussed in a later section.

Reference 2 computed Z_{90} with wavelength for various oceanic and coastal waters. Figure 1 shows these results. The various water types are described in reference 3. Type I waters are very clear ocean waters similar to the Sargasso Sea. Type III water is more turbid such as that found off northeastern South America Types 1 to 9 are coastal waters with type 9 being the most turbid. Types 1 to 9 were derived from observations along the coasts of Scandinavia and western North American. Z_{90} curves for estuaries and continental shelf waters off the East and Gulf Coasts of the United States are not available. The results shown in figure 1 are based on the quasi-single-scattering model described in reference 4. Reference 2 indicates that Z_{90} from the quasi-single-scattering model is within 10 percent of that of multiple scattering Monte Carlo model techniques.

Upwelling Z_{90} is a desired parameter when one is making remote sensing measurements in a particular body of water such that the effect of vertical concentration gradients and bottom reflectivity can be included in the interpretation of the remote sensing data. Comparison of maximum Z_{90} with the one-percent photic zone depth (that layer which attenuates 99 percent of the downwelling light) from reference 3 gives the following results:

Water Type	Max Z_{90} (m)	Max Photic Zone Depth (m)	% of Photic Zone Depth
I	54.0	142.0	38
II	16.0	72.0	22
III	8.4	40.0	21
1	8.2	40.0	21
9	1.8	8.0	23

For turbid ocean and coastal waters, Z_{90} is on the order of 20 percent of the photic zone depth. It should be noted that the wavelength of maximum Z_{90} and maximum photic zone depth varies as water type is changed. For type I water, figure 1 and reference 3 show that maximum values for Z_{90} and photic zone depth occur at approximately 465 nm. As the water becomes more turbid, maximum penetration shifts toward the green with maximum values for Z_{90} and photic zone depth being between 500 nm and 580 nm for coastal water types.

ESTIMATES FOR SPECIFIC WATERS

For pure water with no suspended solids, (little scattering), reference 2 indicates that Z_{90} is given by:

$$Z_{90} = \frac{1}{a_w} \tag{1}$$

where a_w = absorption coefficient in m^{-1}.

When the water contains suspended solids, scattering is increased and Z_{90} is a function of the absorption coefficient, the scattering coefficient, and the type of light (wavelength and whether diffuse or collimated) entering the water. Reference 2 presents a nondimensional chart which gives Z_{90} as a function of the ratio of scattering-to-absorption coefficients (s/a) for red and blue light assuming the ratio of the volume-scattering function to the scattering coefficient is similar to that of the Sargasso Sea. Figure 2(a) shows this chart. It should be noted that as scattering is increased, Z_{90} is reduced. Figure 1 indicates that maximum Z_{90} values occur in the 500-nm to 580-nm range for coastal waters. For an average value at 540 nm, Z_{90} values are similar to those in the 632-nm to 655-nm range for type 7 and 9 waters. For purposes of making a crude approximation, it is assumed in this study that, for all types water, green light at 540 nm acts like red light at 632 nm to 655 nm. Figure 2(b) gives estimated Z_{90} values based on this assumption for the collimated light case.

Z_{90} may be expressed as:

$$Z_{90} = \frac{g}{a} \tag{2}$$

where: $g = f(s/a)$

a = absorption coefficient for mixture

s = scattering coefficient for mixture

For green light, figure 2(b) suggests that $g = 1$ when $s/a = 0$ and is less than 1 for finite scattering. For $s/a = 20$, $g = 0.65$ for collimated light. On a clear sunny day, sunlight incident to the water surface is collimated and 3 to 6 times more intense than the diffuse skylight from background haze. Diffuse skylight is ignored for the remainder of this study, and estimates are based on optical properties of various water mixtures considering collimated light at 540 nm wavelength.

Equation (2) can be used to estimate Z_{90} for specific coastal water bodies if the absorption, scattering, and/or attenuation coefficient for the water mixture are known. Fortunately, such optical properties can be estimated from reference 1 data for the 540-nm wavelength. In reference 1, results are presented from a series of large tank tests in which natural waters were successively concentrated with sediments taken from the bottom of each coastal site location. For each concentration, the attenuation coefficient, α, and the absorption coefficient, a, were measured using a 540 nm collimated laser as the light source. Cross-plots of α versus a showed linear relationships. Values are presented for mixture attenuation coefficient, α, for various sediment concentrations and scattering-to-absorption ratio of sediments, s_{sed}/a_{sed}, at sites in Boston Harbor, Long Island Sound, Delaware Bay, Chesapeake Bay, Baltimore Harbor, Miami Harbor, Mississippi River Delta, and Barataria Bay, Louisiana.

In order to use the reference 1 data in equation (2), the absorption coefficient and the scattering-to-absorption coefficient ratio, s/a, for the water-sediment mixture must be obtained. Assuming scattering in the water to be small compared to that of the particles,

$$\alpha = a + s = a_w + a_{sed} + s_{sed} \tag{3}$$

$$\alpha - a_w = a_{sed} + s_{sed} = a_{sed}\left(1 + \frac{s_{sed}}{a_{sed}}\right) \tag{4}$$

or

$$a_{sed} = \frac{\alpha - a_w}{1 + \frac{s_{sed}}{a_{sed}}} \tag{5}$$

assuming a_w to be approximately 0.07 m^{-1} (ref. 5),

$$s_{sed} = \alpha - \left[0.07 + \left(\frac{\alpha - 0.07}{1 + \frac{s_{sed}}{a_{sed}}}\right)\right] \tag{6}$$

now

$$a = a_w + a_{sed} = 0.07 + \left(\frac{\alpha - 0.07}{1 + \frac{s_{sed}}{a_{sed}}}\right) \tag{7}$$

$$s = s_{sed} \tag{8}$$

$$\frac{s}{a} = \frac{\alpha - \left[0.07 + \left(\frac{\alpha - 0.07}{1 + \frac{s_{sed}}{a_{sed}}}\right)\right]}{0.07 + \left(\frac{\alpha - 0.07}{1 + \frac{s_{sed}}{a_{sed}}}\right)} \tag{9}$$

where α and $\frac{s_{sed}}{a_{sed}}$ values are taken from reference 1.

Equations (7) and (9) give a and s/a from values of α and s_{sed}/a_{sed}. Since Delaware Bay values for a_w ($0.07\ m^{-1}$) are used in this calculation, variations in absorption from dissolved substances and biological activity between the various water bodies are ignored. Table 1 shows results of applying the reference 1 data to equation (7) and (9). Note that s_{sed}/a_{sed} varies for different geographic locations, and that s/a of the water mixture is significantly lower than that of the sediment alone. As sediment concentration increases, the scattering coefficient increases at a much faster rate than the absorption coefficient. For the higher sediment concentration, the absorption of the water alone ($0.07\ m^{-1}$) is small in comparison to the absorption of the sediment. The attenuation coefficient varies with sediment concentration as has been shown by previous authors (ref. 6, for example).

Results from table 1 were applied to figure 2(b) and equation (2) to estimate the Z_{90} values shown in table 2. For ease of comparison, the clear-sky values are correlated with sediment concentration in figure 3. Sediment composition and type has a major influence on penetration depth when concentrations are less than 5 mg/ℓ. For higher sediment concentrations, type and composition do not seem as important as concentration level. The assumption of $0.07\ m^{-1}$ for a_w does not have a significant effect on Z_{90} for sediment levels above 5 mg/ℓ. Z_{90} values for low sediment concentrations are subject to significant error because of this assumption, however.

DISCUSSION

In spite of the approximations of this study, the results in figure 3 are of use to the environmental engineer seeking to quantify water quality parameters from spectroradiometric data. For rivers and estuaries in which sediment concentrations are in excess of 5 mg/ℓ, Z_{90} is less than 2 m. Since these calculations represent near-maximum values at 540 nm, remote sensing depths at other wavelengths are also less than 2 m. If one is investigating parameters which do not have large vertical gradients near the surface (such as some suspended solids), then data analysis techniques which use radiance values from combinations of bands (such as refs. 6 and 7) are physically appropriate since each wavelength is seeing a similar concentration level near the surface, For coastal waters with large remote sensing depths, vertical changes in concentration level may cause difficulties with multi-wavelength data analysis techniques unless bands are selected which have near-equal penetration depths.

Many publications (refs. 1, 8, and 9 for example) make the assumption that scattering from the water (molecular scattering) is small in comparison to scattering from suspended sediment. Reference 10 gives data for both distilled water and Chesapeake Bay water (unknown sediment concentration). At 540 nm, the scattering coefficient of distilled water is 0.01 m^{-1} which is small in comparison to the scattering coefficients for the various coastal sediment concentrations shown in table 1. It should be noted that reference 10 shows the absorption coefficient of distilled water to be 0.033 m^{-1} which is half the 0.07 m^{-1} value of Delaware Bay. Thus the Delaware Bay value includes the effects of dissolved substances. Reference 10 shows the absorption coefficient for continental shelf waters 2.5 miles off the coast of Hollywood, Florida to be 0.1 m^{-1} at 540 nm. The scattering coefficient for the Florida water was also 0.1 m^{-1}, which means that molecular scattering from the water ($\sim$ 0.01 m^{-1}) becomes more important in continental shelf and oceanic waters with sediment concentrations less than 0.5 mg/ℓ.

It is recognized that coastal waters are usually not homogenous in the vertical direction. Future Z_{90} calculations should be made considering the effects of vertical gradients in the water columns. For the larger sediment concentrations, the remote sensing depth may be small enough that vertical gradients are not a serious problem. Z_{90} estimates are needed for sediment concentrations in the 5.0 to 100.0 mg/ℓ range to assess the influence of vertical gradients in highly turbid waters.

CONCLUDING REMARKS

Under the assumption of collimated light, a homogenous water column, zero molecular scattering, and constant ratio of volume scattering function to scattering coefficient, estimates of the remote sensing depth parameter, Z_{90}, are made for various coastal waters at a wavelength of 540 nm. Variations in absorption due to dissolved substances and biological productivity are ignored. While the estimates are quite crude, the influence of sediment type and concentration on remote sensing depth is demonstrated.

Calculations indicate that sediment composition and type have a strong influence on Z_{90} when concentrations are below 5 mg/ℓ. The absorption coefficients of the sediments become large in comparison to that of water causing Z_{90} values to be less than 2 m with only small differences between various sediment types. Based on the need for environmental engineers to know depth of penetration for various wavelengths for various types of sediments, future work is needed to more accurately define Z_{90} for sediment concentrations up to 100 mg/ℓ.

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TABLE 1

OPTICAL PROPERTIES FOR VARIOUS COASTAL WATERS

AT 540 NM WAVELENGTH

Location	Sediment Concentration (mg/ℓ)	$(s/a)_{sed}$ (ref. 1) (m^{-1})	(s/a) (m^{-1})	s_{sed} (m^{-1})	a (m^{-1})	α (ref. 1) (m^{-1})
Boston Harbor	2.53	5.9	2.7	0.36	0.13	0.49
	3.30	5.9	3.8	0.74	0.20	0.94
	4.20	5.9	4.7	1.61	0.34	1.95
	8.08	5.9	5.2	3.03	0.59	3.62
Long Island	1.40	5.0	2.9	0.50	0.16	0.66
	1.60	5.0	3.5	0.83	0.24	1.07
	2.70	5.0	4.1	1.55	0.38	1.93
	3.80	5.0	4.2	1.90	0.45	2.35
Delaware Bay	0.50	5.0	2.2	0.28	0.12	0.40
	1.90	5.0	3.4	0.78	0.22	1.00
	2.90	5.0	4.1	1.61	0.39	2.00
	25.00	5.0	4.6	4.10	0.89	5.00
Chesapeake Bay	1.00	5.3	2.6	0.37	0.14	0.51
	1.60	5.3	3.6	0.77	0.22	0.99
	2.70	5.3	4.3	1.66	0.39	2.05
	9.50	5.3	4.7	3.30	0.70	4.00
Baltimore Harbor	2.30	3.3	2.9	1.48	0.52	2.00
	5.30	3.3	3.1	3.02	0.98	4.00
Miami Harbor	2.67	5.9	3.0	0.42	0.14	0.56
	3.47	5.9	3.9	0.79	0.20	0.99
	4.50	5.9	4.7	1.69	0.36	2.05
	18.00	5.9	5.5	5.15	0.94	6.10
Mississippi Delta	11.40	9.1	7.8	3.81	0.49	4.30
Barataria Bay	3.00	12.5	7.9	1.51	0.19	1.70
Marl		5.6				
Quartz		16.7				

TABLE 2

ESTIMATED Z_{90} VALUES FOR VARIOUS COASTAL WATERS

AT 540 NM WAVELENGTH

Location	Sediment Concentration (mg/ℓ)	Clear Sky Max Z_{90} (m)
Boston Harbor	2.53	6.7
	3.30	4.3
	4.20	2.4
	8.08	1.4
Long Island	1.[illegible]0	5.2
	1.[illegible]	3.6
	2.[illegible]0	2.2
	3.80	1.9
Delaware Bay	0.50	7.1
	1.90	3.8
	2.90	2.2
	25.00	0.9
Chesapeake Bay	1.00	6.3
	1.60	3.9
	2.70	2.2
	9.50	1.2
Baltimore Harbor	2.30	1.7
	5.30	0.9
Miami Harbor	2.67	6.2
	3.47	4.2
	4.50	2.3
	18.00	0.8
Mississippi	11.40	1.6
Barataria Bay	3.00	3.9

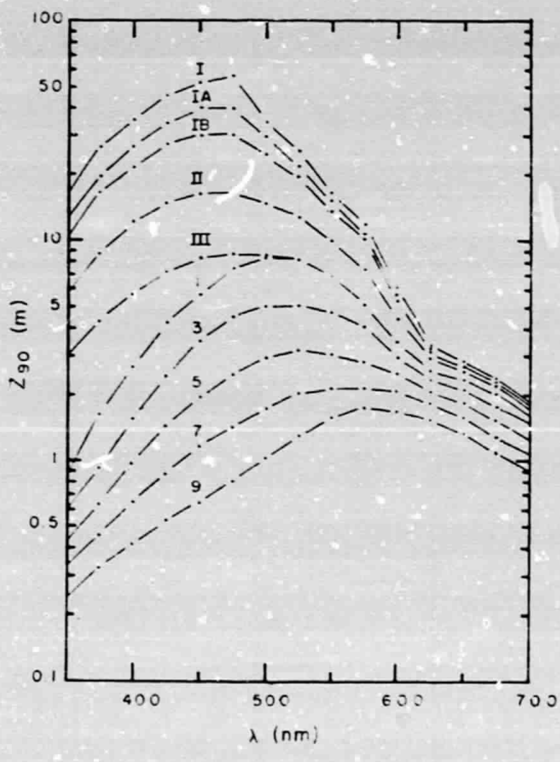
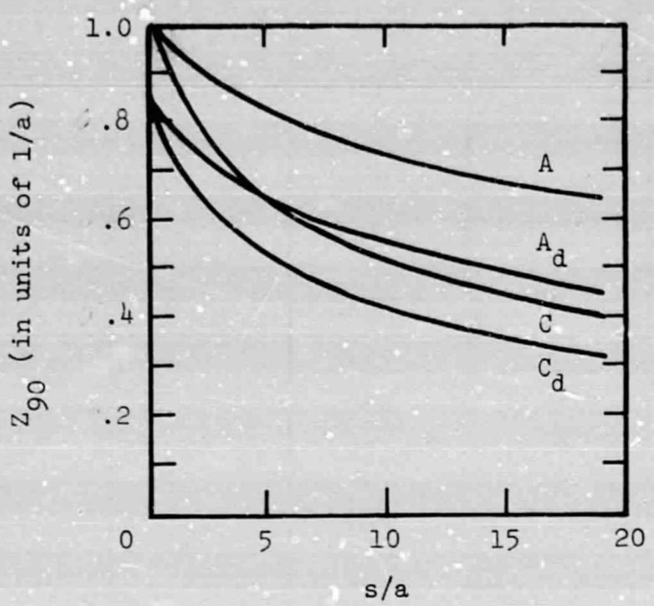


Figure 1.- Variation of Z_{90} for various water types (ref. 2).



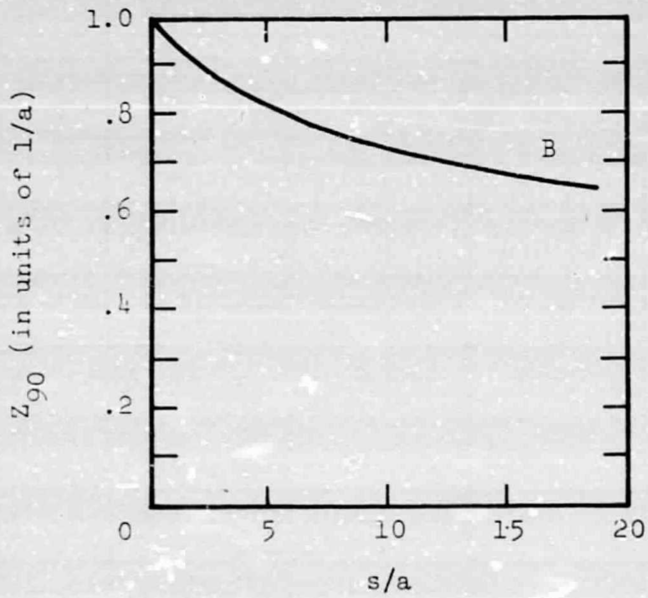
A = Collimated light at 632-655 nm

A_d = Diffuse light at 632-655 nm

C = Collimated light at 460 nm

C_d = Diffuse light at 460 nm

(a) Z_{90} for red and blue light (ref. 2).



B = Collimated light at 540 nm

(b) Estimated Z_{90} for green light.

Figure 2.- Z_{90} as a function of absorption coefficient, scattering coefficient, and incident light.

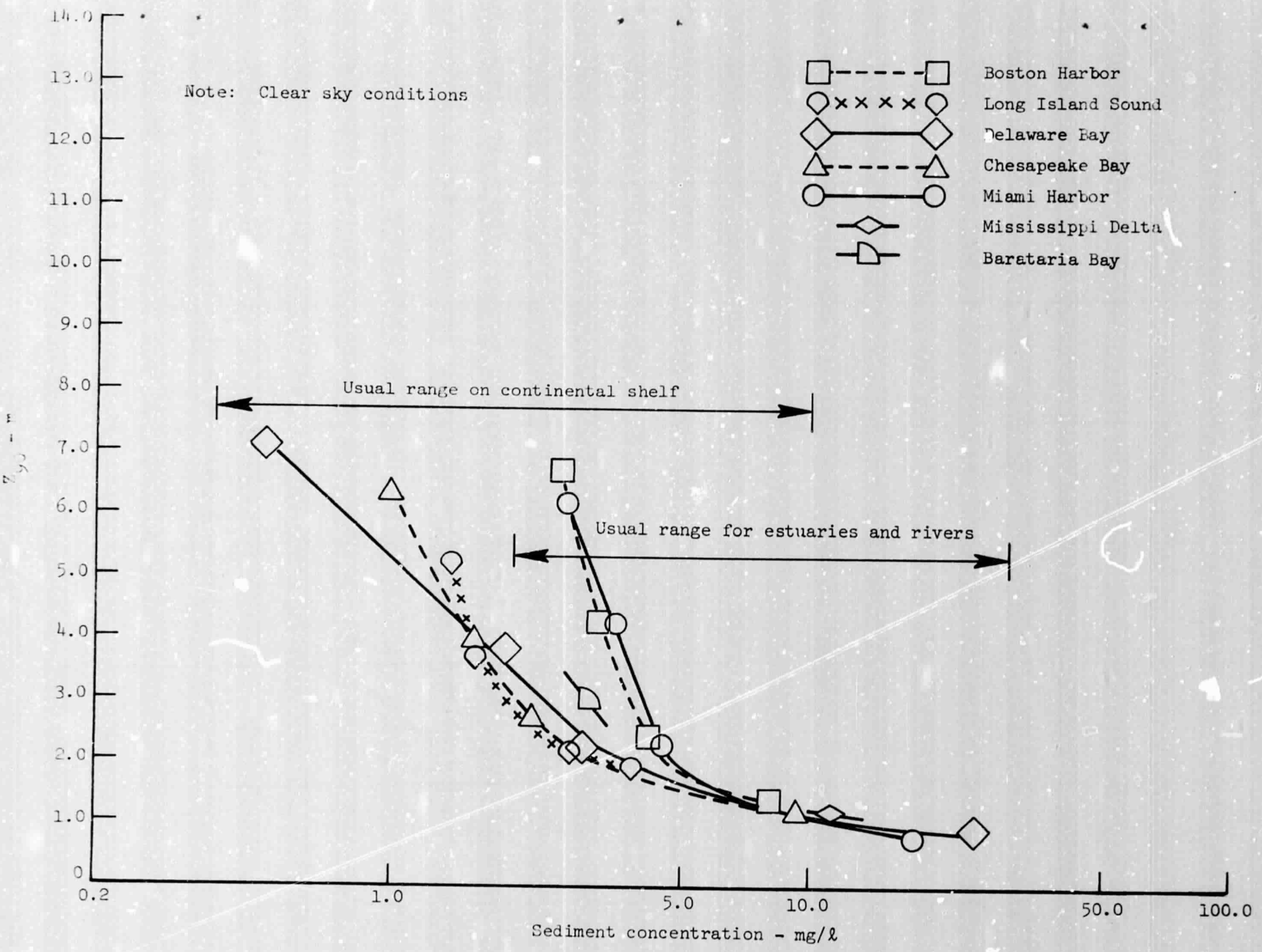


Figure 3.- Comparison of Z_{90} at 540 nm for various sediment concentrations.