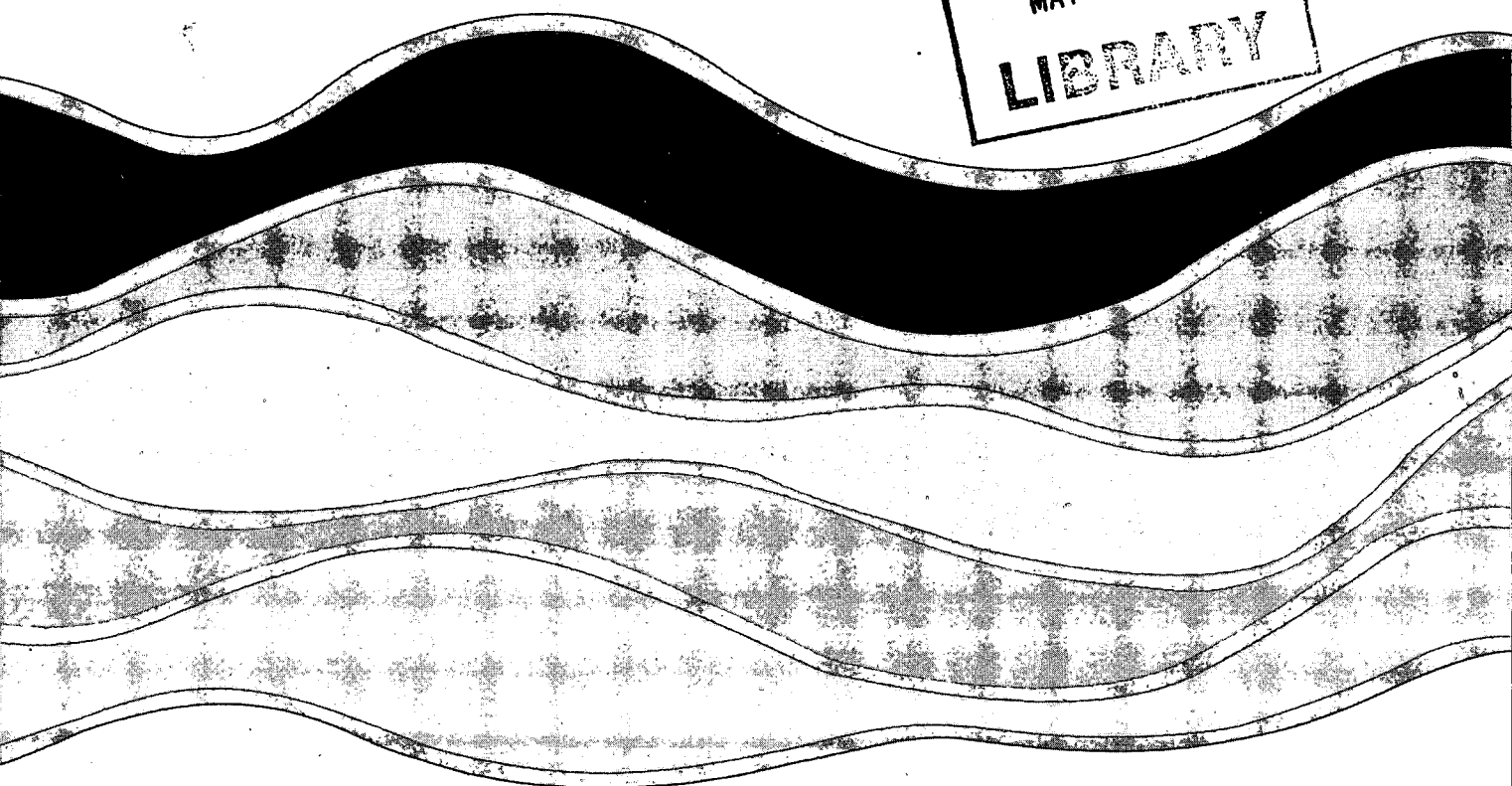
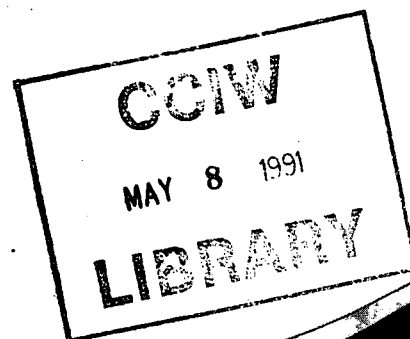
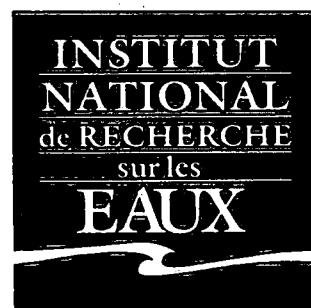
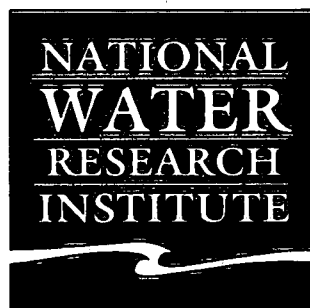


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SPACE MONITORING OF OPTICALLY-ACTIVE COMPONENTS
OF INLAND WATERS: AN ESSENTIAL COMPONENT OF
REGIONAL CLIMATE CHANGE IMPACT STUDIES

R.P. Bukata, J.H. Jerome, K. Ya. Kondratyev
and D.V. Pozdnyakov

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**SPACE MONITORING OF OPTICALLY-ACTIVE
COMPONENTS OF INLAND WATERS: AN ESSENTIAL
COMPONENT OF REGIONAL CLIMATE CHANGE IMPACT STUDIES**

by

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MANAGEMENT PERSPECTIVE

The upcoming decades will witness large scale multinational and multidisciplinary programs dedicated to the monitoring and assessment of climate change impacts upon the environment. Central to such assessment programs is the need to reliably estimate bioproductivity from space. Considerable successes are being achieved in estimating such bioproductivity over land masses (agriculture and forestry) and over large water masses (oceanography). To date, space mapping of chlorophyll concentrations from waters strongly influenced by land masses (lakes, rivers, estuaries, coastal regions), however, has been surprisingly ignored within the overall scenario of global climate change impact studies. The optical complexities comprising limnological and coastal water masses present considerably more obstacles to space monitoring of aquatic bioproductivity than do the less complex mid-ocean water masses. The NWRI optical cross sections model has been designed to overcome many of these obstacles.

Data from Lake Ladoga in the Soviet Union are used to illustrate that the NWRI model could successfully estimate limnological chlorophyll concentrations while six different oceanic models in current use could not.

A strong recommendation is made by the Rivers Research Branch of NWRI and the Institute for Lakes Research of the USSR Academy of Sciences that a) space monitoring of limnological chlorophyll be incorporated into programs of regional climate change impact studies in the same manner as space monitoring of oceanic chlorophyll is being incorporated into programs of global climate change impact studies, and b) that cross sections be determined for the optically-active

components of every major inland and coastal water body. Such activities are consistent with the objectives of the International Geosphere-Biosphere Program.

PERSPECTIVE GESTION

Les prochaines décennies verront des programmes multinationaux et pluridisciplinaires de vaste envergure consacrés à la surveillance et à l'évaluation des incidences du changement climatique sur l'environnement. La nécessité d'évaluer sérieusement la productivité biologique à partir de l'espace est au coeur de ces programmes d'évaluation. L'estimation de la productivité biologique de zones terrestres (secteur agricole et forestier) et de vastes étendues d'eau (océanographie) a donné de bons résultats. Toutefois, il est surprenant de constater que la cartographie spatiale des concentrations de chlorophylle dans les plans d'eau fortement influencés par des zones terrestres (lacs, rivières, estuaires, régions côtières) a été laissée de côté dans le scénario général des études d'impact du changement climatique mondial. Les complexités optiques touchant des étendues d'eau lacustres et des étendues d'eau côtière présentent beaucoup plus d'obstacles à la surveillance spatiale de la productivité biologique aquatique que les étendues d'eau médio-océaniques moins complexes. Le modèle optique relatif à des vues en coupe de l'INRE a été conçu afin de surmonter ces obstacles.

Les données du lac Ladoga (Union soviétique) sont utilisées pour montrer que le modèle de l'INRE permet d'estimer des concentrations de chlorophylle dans les lacs contrairement à six modèles océaniques différents présentement utilisés.

La Direction de la recherche sur les cours d'eau de l'INRE et l'Institut de recherche sur les cours d'eau de l'Académie des sciences des l'URSS recommandent fortement que a) la surveillance spatiale de

la chlorophylle dans les eaux lacustres soit incorporée dans les programmes d'études d'impact du changement climatique régional de la même façon que la surveillance spatiale de la chlorophylle dans l'océan, dans les programmes d'études d'impact du changement climatique mondial, et b) les vues en coupe soient établies pour des composantes optiquement actives de chaque grand plan d'eau intérieur et côtier. De telles activités sont conformes aux objectifs du Programme international géosphère-biosphère.

ABSTRACT

Consistent with the climate change objectives of the IGBP is the need to remotely monitor and map both global and regional biological productivity over lands, oceans, and inland waters. Models and algorithms are currently being developed to infer aquatic primary production from near-surface chlorophyll concentration values determined from satellite sensors. Data from Lake Ladoga are utilized to illustrate that the algorithms currently being used to space monitor near-surface chlorophyll concentrations in oceanic waters are inadequate when applied to water masses optically complicated by their proximity to land masses. Methodologies originally developed for retrieving simultaneous concentrations of chlorophyll, suspended minerals, and dissolved organic carbon from volume reflectance measurements of Lake Ontario are shown to display success in Lake Ladoga that could not be duplicated by six different oceanic chlorophyll retrieval algorithms. The principal requirements for water quality space monitoring are the cross sections of the optically-active components of the water body being remotely monitored. It is argued that, despite the spatial and temporal variability of such cross sections, their determination for principal water bodies should comprise both global and regional climate change studies.

RÉSUMÉ

Conformément aux objectifs du PIGB concernant le changement climatique, il est nécessaire de surveiller et de cartographier à distance la productivité biologique globale et régionale des terres, des océans et des eaux intérieures. Des modèles et des algorithmes sont en voie d'élaboration afin de déterminer la production primaire aquatique à partir de concentrations de chlorophylle mesurées à faible profondeur et établies à partir de sondes satellitaires. Les données du lac Ladoga sont utilisées pour montrer que les algorithmes utilisés présentement pour surveiller à partir de l'espace les concentrations de chlorophylle à faible profondeur dans les océans ne conviennent pas lorsqu'ils sont appliqués à des étendues d'eau optiquement complexes en raison de leur proximité des zones terrestres. Des méthodes conçues au départ pour extraire les concentrations simultanées de chlorophylle, de minéraux en suspension, et de carbone organique dissous des mesures du pouvoir de réflexion volumique du lac Ontario montrent de bons résultats dans le cas du lac Ladoga, résultats qui ne peuvent pas être répétés par six algorithmes d'extraction différents pour la chlorophylle dans les océans. Les principales exigences de la surveillance spatiale de la qualité de l'eau sont les vues en coupe des composantes optiquement actives du plan d'eau surveillé à distance. On soutient que, malgré la variabilité spatiale et temporelle de ces vues en coupe, leur établissement pour les principaux plans d'eau devrait comprendre des études du changement climatique global et régional.

INTRODUCTION

The earth is currently subject to both natural and anthropogenic climate changes which have necessitated global participation in ecosystem solar/terrestrial research programs of unprecedented complexities. That the terrestrial water masses comprise a principal target for such ecosystem studies is undeniable. The exact roles of aquatic resources in the responsive and/or proactive feedback loops within the terrestrial environment, while generally understood and appreciated, are still not uniquely defined in terms of cause/effect relationships. With the advent of global climatology programs such as the International Geosphere-Biosphere Program (IGBP), the Global Change: Impact on Habitability (GCIH) and the World Ocean Circulation Experiment (WOCE) and their key dependence upon reliable measurements from space platforms, the need for converting such space-acquired data into environmentally significant parameters required for the prediction or assessment of climate change impacts is dramatically accentuated.

Remote sensing devices record the electromagnetic emanations (either passive or active) from some combination of the organic and/or inorganic components of the biosphere. No per se environmental information is directly collected. Consequently, the electromagnetic information must be converted, through appropriate multidisciplinary modelling activities into inferred estimates of the chemical, physical, or biological variables being sought. The successes or failures of satellites in evaluating environmental impacts, therefore, are clearly dependent upon the models and algorithms developed and used for the extraction of environmental parameters from the continuum of spectro-optical data collected by the terrestrial satellites.

Of particular concern to both IGBP and GCIH (National Research Council, 1983; NASA, 1982; 1983) are the anthropogenic impacts on the biogeochemical cycles of carbon, nitrogen, sulfur, phosphorus, and water, in addition to such environmental health indicators as solar radiation, water quality, air quality, and soil fertility. Regarding the remote sensing of environmental parameters from space, the IGBP strategy is to divide environmental problems into the general categories agriculture, forestry, geology, hydrology, and oceanology. Within the category oceanology, specific problems include:

- a) Sea surface state
- b) Sea ice
- c) Aquatic turbidity
- d) Coastal tides and currents
- e) Global-scale currents
- f) Distribution and migration of aquatic organisms
- g) Coastal aquatic contamination
- h) Near-shore processes
- i) Bathymetry and topography of ice
- j) Coastline mapping
- k) Bars, reefs, and shoals

Such specific oceanographic problems, however, should not be considered in preclusion of their limnological counterparts since global climate change is intimately linked with regional climate change.

An essential requirement for the assessment and prediction of the impacts of both global and regional climate change on the earth's

aquatic resources is the ability to determine and record:

- 1) Changes in the inputs of the biogenic components (nitrogen, sulfur, phosphorus) as well as toxic rain and heavy metal and oxidant depositions;
- 2) the impact of such biogenic changes on both large volume and small volume carbon reservoirs such as oceans, lakes, rivers, and estuaries;
- 3) the reaction of aquatic biota to climate change;
- 4) the temporal history of the organic and inorganic composition of the aquatic resources, i.e. reliable determinations of the simultaneous concentrations of such aquatic components as chlorophyll, suspended sediments and dissolved organic matter.

Therefore, the problems of biological productivity on land and in water assume paramount importance. For the case of regional water resources, biological productivity assessment in the upcoming decades will require the ability to accurately monitor from space the level of such aquatic productivity while simultaneously monitoring from space the quality of the water as a function of both space and time. This requires the ability to distinguish at any given time and place the principal organic and/or inorganic components, in particular the chlorophyll, suspended sediment and dissolved organic matter concentrations, characterizing the water body being remotely sensed. This, in turn, requires the existence of reliable water quality parameter retrieval algorithms coupled with whatever invariant aquatic properties are required as input to such retrieval algorithms.

MAPPING AQUATIC BIOLOGICAL PRODUCTIVITY

The Coastal Zone Color Scanner (CZCS) launched aboard NIMBUS-7 in 1978 has enabled an assessment of oceanic phytoplankton biomass (Putnam, 1987). Satellite-based observations, however, are restricted to the upper one attenuation length of a water body's depth. To characterize a water column on the basis of its near-surface layer is certainly non-optimal. Techniques must therefore be developed from which primary production of the entire water column may be inferred from near-surface chlorophyll observations.

The two most significant factors governing the photosynthetic processes in natural water bodies are the nature and intensity of the impinging photon flux, and the degradation of this flux in its subsurface propagation. This latter factor is directly controlled by the concentrations and optical properties of the organic and inorganic matter comprising the water column. A wealth of valuable literature exists proposing mathematical methods for estimating primary production, a representative sample of which would include Smith (1936), Talling (1957), Vollenweider (1965), Fee (1969), Bannister (1974) and others reviewed in Vollenweider (1965) and Patten (1968). Recent works (Kirk, 1984; Jerome et al. 1988; Bukata et al. 1989; Sathyendranath and Platt, 1989 (a); Bannister, 1990) have considered the impacts on irradiation and primary production of using a time-dependent attenuation coefficient (i.e. incorporating the effects of solar angle and latitude) in such determinations.

The development of algorithms which would yield aquatic primary production as a function of near-surface chlorophyll distribution is, of course, further complicated by the non-uniform vertical profiles of

pigment concentration defining natural water masses. Algorithms for overcoming such non-uniform chlorophyll concentration profiles have been discussed by Platt and Sathyendranath (1988) and Sathyendranath and Platt (1989b).

For such algorithms to be effective, the chlorophyll mapping capabilities must, of course, be reliable.

ESTIMATING WATER QUALITY FROM SPACE

For nearly two decades chlorophyll concentrations in oceans have been estimated from remotely-sensed data with reasonable accuracy. Chlorophyll retrieval algorithms are generally based upon appropriate ratios of spectral radiances recorded at satellite or aircraft altitudes (Gordon and Clark, 1980; Gordon et al. 1983; Morel, 1980; Smith and Wilson, 1981; amongst others). Expressed as functions of upwelling radiances $L(\lambda)$, such algorithms assume the form

$$C = x_1 \left(\frac{L(\lambda_1)}{L(\lambda_2)} \right)^{x_2} \quad (1)$$

where C = chlorophyll concentration

$L(\lambda_1)$ and $L(\lambda_2)$ = upwelling radiance at two different wavelengths
 λ_1 and λ_2

x_1 and x_2 = empirically-determined constants.

Such chlorophyll retrieval algorithms are derived solely from regression techniques, and, as such ignore the specific absorption and scattering properties of the water body being remotely-sensed. The success of these algorithms is largely a consequence of the optical simplicity characteristic of mid-ocean and many near-coastal waters. Water bodies strongly influenced by land masses display higher orders of optical complexity. This is a result of an increased number of optically-active components co-existing within the water column, as well as greater ranges in the variations of the concentrations of these aquatic components. The optically-competitive compositions of coastal, estuarial, lake, and river water masses, therefore, prohibits the use of such simplistic oceanic chlorophyll-retrieval algorithms.

The inappropriateness of applying oceanic chlorophyll-retrieval algorithms to inland waters is illustrated in Figure 1. Herein chlorophyll concentrations determined for directly-collected water samples from Lake Ladoga in 1989 are plotted against the chlorophyll concentrations inferred from simultaneously-obtained subsurface optical measurements. Six different ocean retrieval algorithms in widespread use (mathematical expressions are listed in the Figure) were used to predict chlorophyll concentrations. The lack of agreement between the measured and predicted concentrations for each algorithm, as well as the lack of agreement amongst the algorithms themselves, is very apparent.

Figure 2 compares the laboratory determinations of chlorophyll concentrations with the predictions of Lake Ladoga chlorophyll concentrations resulting from the use of the optical water quality model (Bukata et al., 1985) and the Lake Ladoga optical cross sections given in our companion paper (Bukata et al. 1991). The differences

between Figures 1 and 2 are strikingly obvious. For inland waters containing simultaneously varying quantities of chlorophyll-bearing biota, suspended sediments, and dissolved organic matter, it is essential that the observed spectral signatures recorded over such optically-complex targets be unambiguously correlated with these organic and inorganic materials. Such unambiguous correlations require the spectral dependencies of the pertinent optical cross sections (i.e. the amount of scattering and absorption that may be ascribed to a unit concentration of each aquatic component).

A further and major advantage of using the optical cross sections to extract chlorophyll concentrations from inland waters is that simultaneous concentrations of suspended minerals (used as a surrogate for suspended sediments) and dissolved organic carbon (used as a surrogate for dissolved organic matter) may also be inferred from a single determination of the subsurface volume reflectance spectrum $R(\lambda)$ (as illustrated in our companion paper).

Figure 3 shows the comparison between the directly-measured (from the same water samples that were used to generate Figures 1 and 2) suspended mineral concentrations in Lake Ladoga and the suspended mineral concentrations inferred from the optical water quality model. Figure 4 shows the same intercomparison for dissolved organic carbon concentrations.

Consequently, we advocate that

- a) surface chlorophyll mapping of inland waters be incorporated into regional climate change studies in much the same manner as surface chlorophyll mapping of ocean waters has been incorporated into global climate change studies;

- b) optical cross sections be determined for every optically-complex water mass of local, regional and/or global significance since oceanic chlorophyll extraction algorithms cannot be utilized to provide reliable chlorophyll mapping capabilities for such waters.

The multivariate optimization analyses for determining optical cross section spectra and utilizing these cross section spectra to extract simultaneous concentrations of water quality indicators from measurements of subsurface volume reflectance spectra have been briefly reviewed in the companion paper (Bukata et al. 1991). In order to apply the optical water quality model to space-acquired data, the subsurface volume reflectance spectrum must first be transferred through the air-water interface (as discussed in Bukata et al. 1988), and, in conjunction with appropriate atmospheric models (Kondratyev, 1969; Gordon et al., 1988; Viollier et al., 1980; Arnone and LaViolette, 1984) be transferred through the atmosphere to aircraft or satellite altitudes. These activities are shown in the flow diagram of Figure 5.

GLOBAL MEASUREMENTS OF CHLOROPHYLL CROSS SECTIONS

While there is an increasing effort, on a global scale, to obtain precise information on the optical cross sections of chlorophyll-bearing biota, the results of such efforts have been far from universally applicable. Certainly there has been general agreement concerning rather broad (in some cases) ranges of values of such cross sections, as well as the realization that such optical cross sections are species dependent, and therefore temporally and

spatially dependent. Consequently, a major obstacle to the remote estimation of aquatic chlorophyll from space has been a lack of sufficient information on the precise values and variations in the optical cross sections for major inland, estuarial, and coastal waters. Such temporal and spatial determinations are mandatory if the oceanic and agricultural productivity remote sensing mapping successes are to be duplicated for the optically complex land-influenced water masses considered here.

Morel and Bricaud (1981) have illustrated that the absorption cross sections of chlorophyll a not only vary from algal species to algal species, but also are strongly dependent upon variations in cell size, cell age and past light history within the cells of the same species.

A typical, but by no means exhaustive, representation of the vast variations that have been observed in the determinations of the absorption cross sections of chlorophyll a (uncorrected for phaeophytins) is shown in Figure 6 wherein are plotted results of various workers. Apart from the Morel (1988) data (Curve 3), which were obtained from laboratory cultures, the absorption cross section curves of Figure 6 were determined from field investigations, and represent waters from such sources as the North Central Pacific, Coastal regions off California, Peruvian upwelling region, the Sargasso Sea, Lake Ladoga, and Lake Ontario. Curve 3 is the average absorption spectrum for fourteen different algal species. Six of the seven curves of Figure 6 display similar spectral shapes, the data from the Sargasso Sea (Curve 5) defining the only obvious exception. Despite the limited data sets depicted in Figure 6, it is noted that the curves representing inland waters (Curves 1 and 2) display

absorption cross section values that are consistently larger at the longer wavelengths than those determined for the oceanic and coastal waters.

CONCLUDING REMARKS

During the upcoming decades considerable global emphasis will be placed upon the impacts of climate change on the earth's aquatic resources. Germane to such environmental impact studies will be the ability to monitor and assess the biological productivity on land and in water. Since aquatic biological productivity may be mathematically modelled in terms of near-surface chlorophyll distributions, the ability to reliably estimate near-surface chlorophyll distributions from remote observation platforms (environmental satellites are a principal component of IGBP, GCIH, and associated multinational programs) assumes paramount importance.

Chlorophyll-retrieval algorithms for ocean waters developed for space vehicles such as NIMBUS-7 are not appropriate for application to chlorophyll retrieval from non-ocean waters. This has been dramatically illustrated by applying to Lake Ladoga a water quality model developed earlier for the optically complex waters of Lake Ontario. The essential requirements for such an optical water quality model are the cross sections of the principal organic and inorganic components of the water body. Once these optical cross sections are obtained, optimization analyses enable the simultaneous estimations of chlorophyll, suspended minerals, and dissolved organic carbon concentrations from a direct measurement or a remote estimate of subsurface volume reflectance.

The need for determining pertinent optical cross sections has been illustrated not only by the success of the model in simultaneously extracting three co-existing water quality concentrations from Lake Ladoga, but also by the failure of six different oceanic algorithms to successfully extract chlorophyll concentrations from these same lake waters. The fact that six different oceanic algorithms yielded chlorophyll concentrations which were themselves in conflict may suggest that such retrieval algorithms may lack sufficient reliability for some ocean monitoring.

The optical cross sections are functions of time and space. Variabilities in the absorption cross sections for chlorophyll as determined by several workers have been shown. Despite such cross section variability, however, we have argued that global measurements of chlorophyll, and, therefore, regional measurements of optical cross sections are essential for the successful interweaving of the role of water resources into multidisciplinary programs of climate change research. Therefore, optical cross sections, along with their seasonal and spatial variabilities, must be determined for each major inland water body. Possibly such optical cross sections should also be determined for oceanic waters.

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FIGURE CAPTIONS

- Figure 1: Directly-sampled chlorophyll concentrations in Lake Ladoga plotted against chlorophyll concentrations predicted by six different contemporary oceanic chlorophyll-retrieval algorithms.
- Figure 2: Directly-sampled chlorophyll concentrations in Lake Ladoga plotted against chlorophyll concentrations predicted by the use of the optical water quality model.
- Figure 3: Directly-sampled suspended mineral concentrations in Lake Ladoga plotted against suspended mineral concentrations predicted by the use of the optical water quality model.
- Figure 4: Directly-sampled dissolved organic carbon concentrations in Lake Ladoga plotted against dissolved organic carbon concentrations predicted by the use of the optical water quality model.
- Figure 5: Flow diagram outlining the activities in the development of remote sensing optical water quality models based upon the specific absorption and scattering cross sections of the aquatic components.
- Figure 6: An intercomparison of a number of independent attempts to determine the absorption cross sections of chlorophyll a (uncorrected for phaeophytins). Data are taken from the current work, Curves 1 and 2; Morel (1988), Curve 3; Smith and Baker (1978), Curve 4; Bricaud and Stramski (1990), Curves 5 and 6; and Mitchell and Kiefer (1988), Curve 7.

FIGURE 1

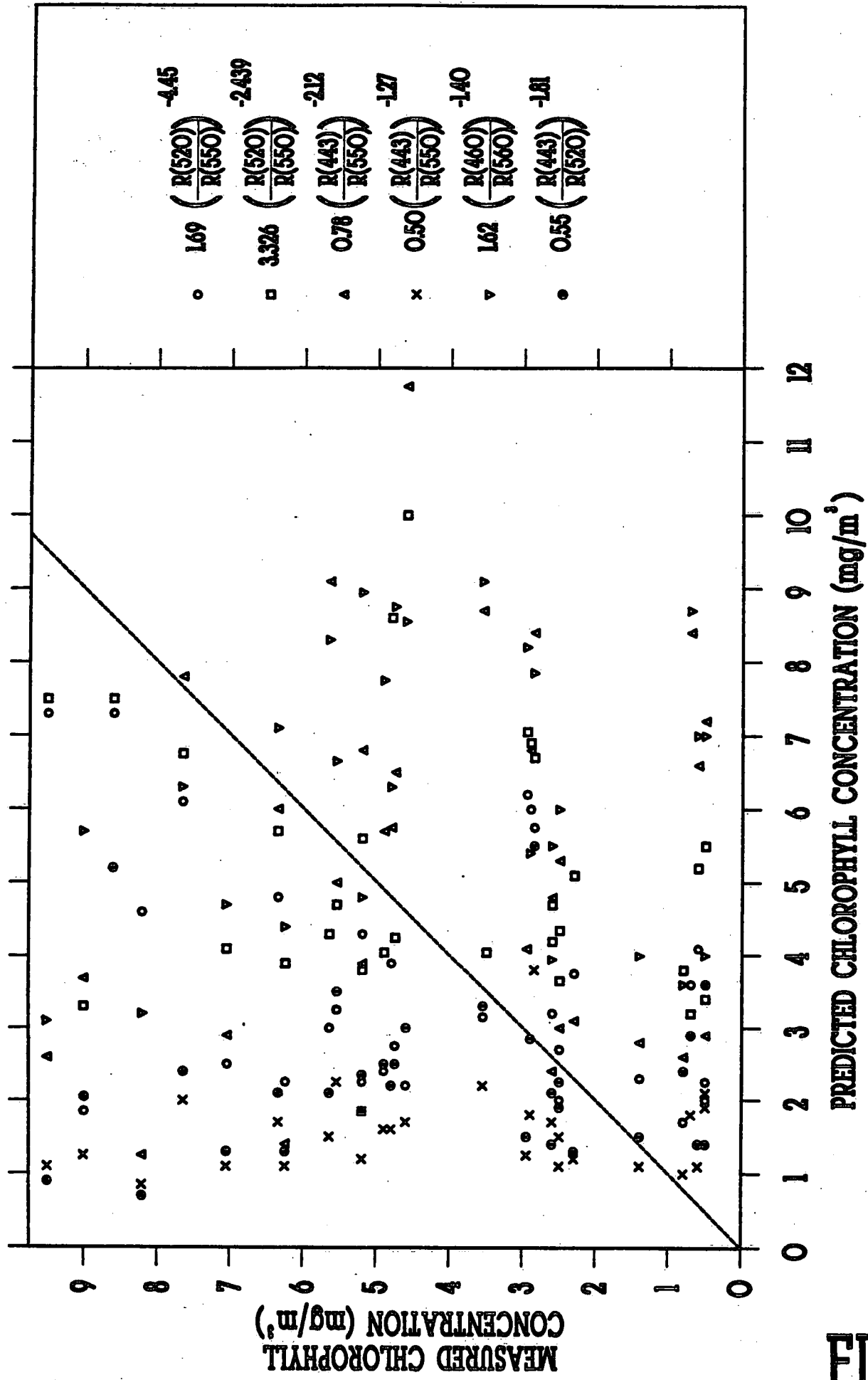
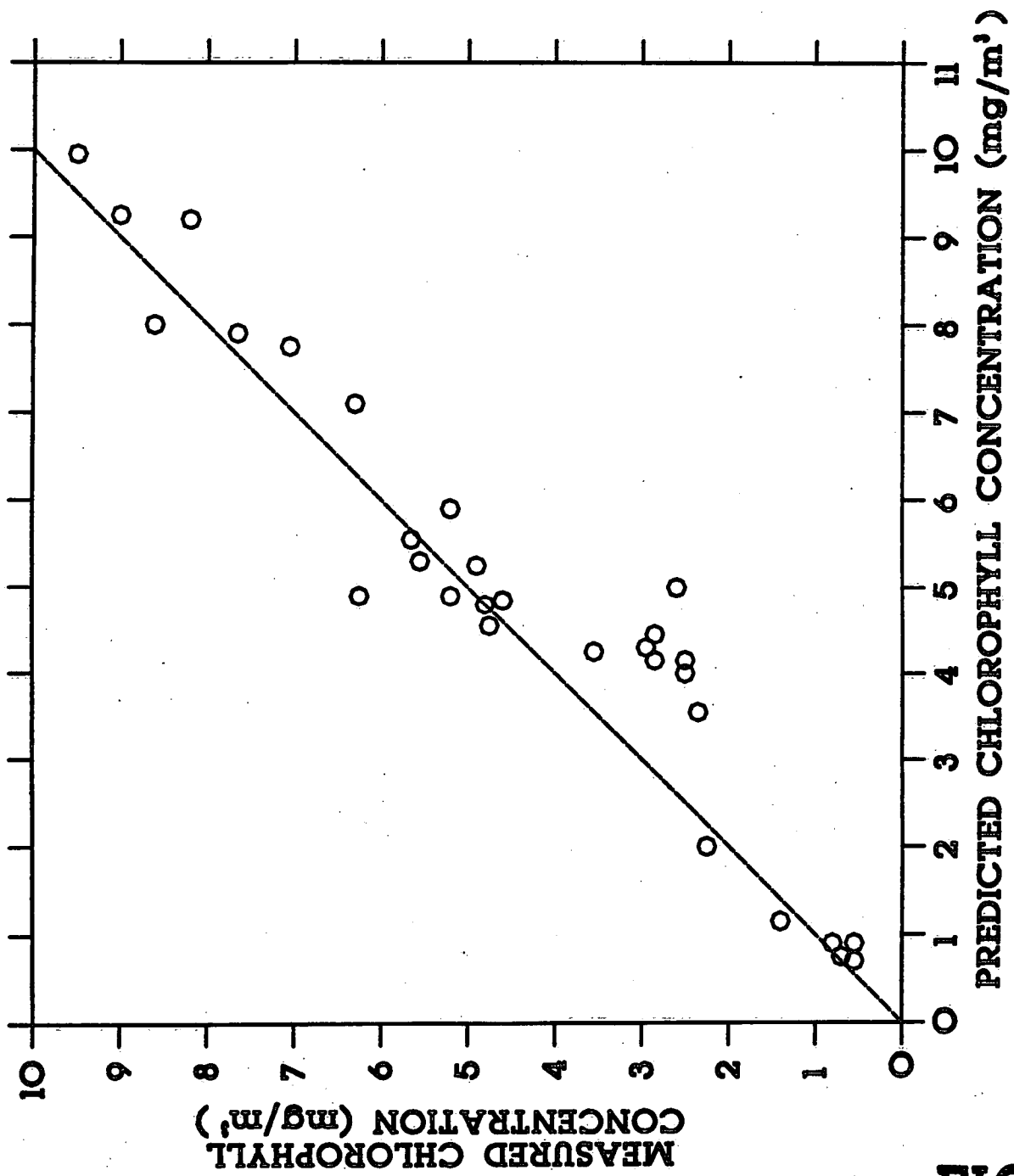


FIGURE 2



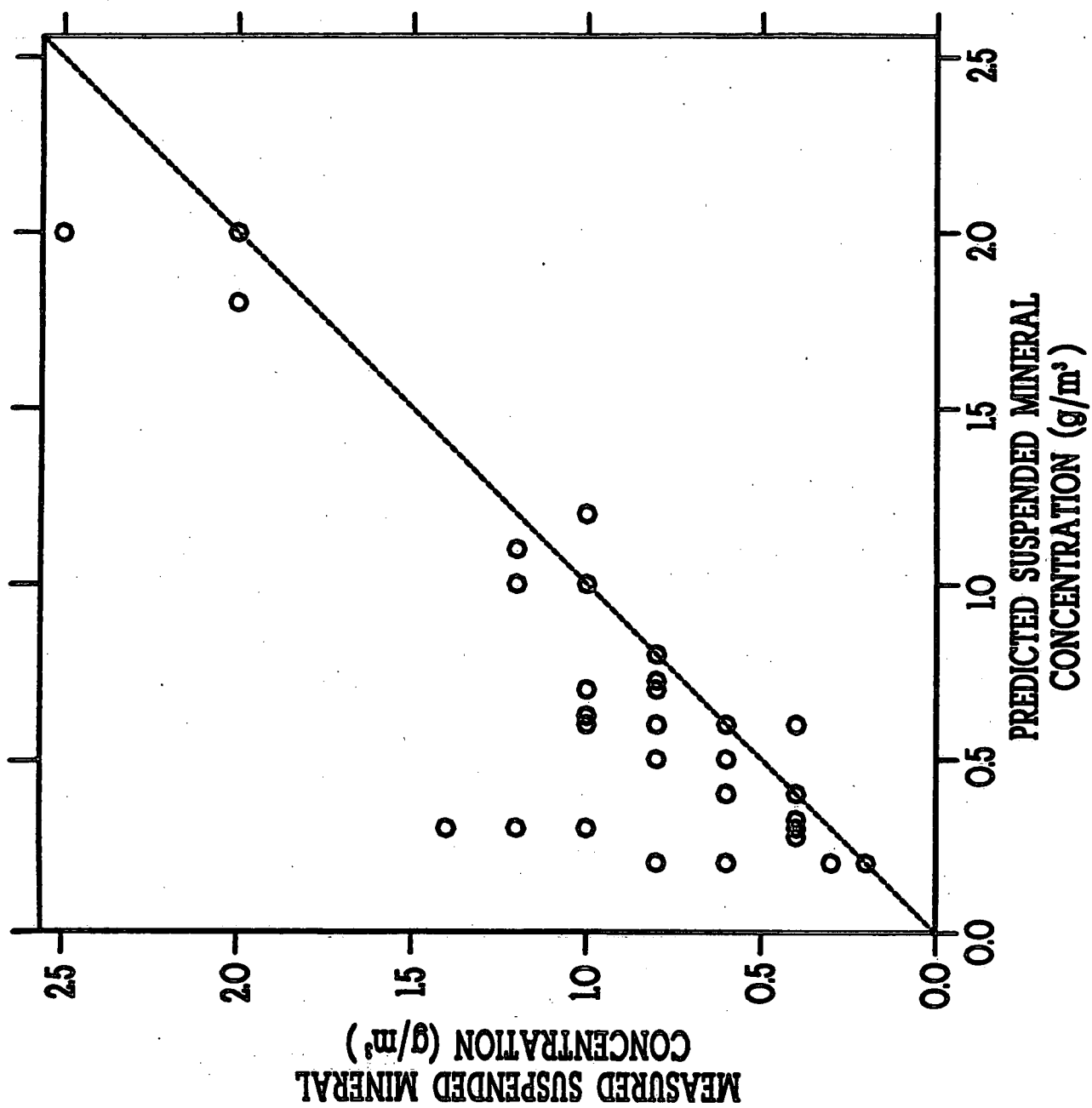


FIGURE 3

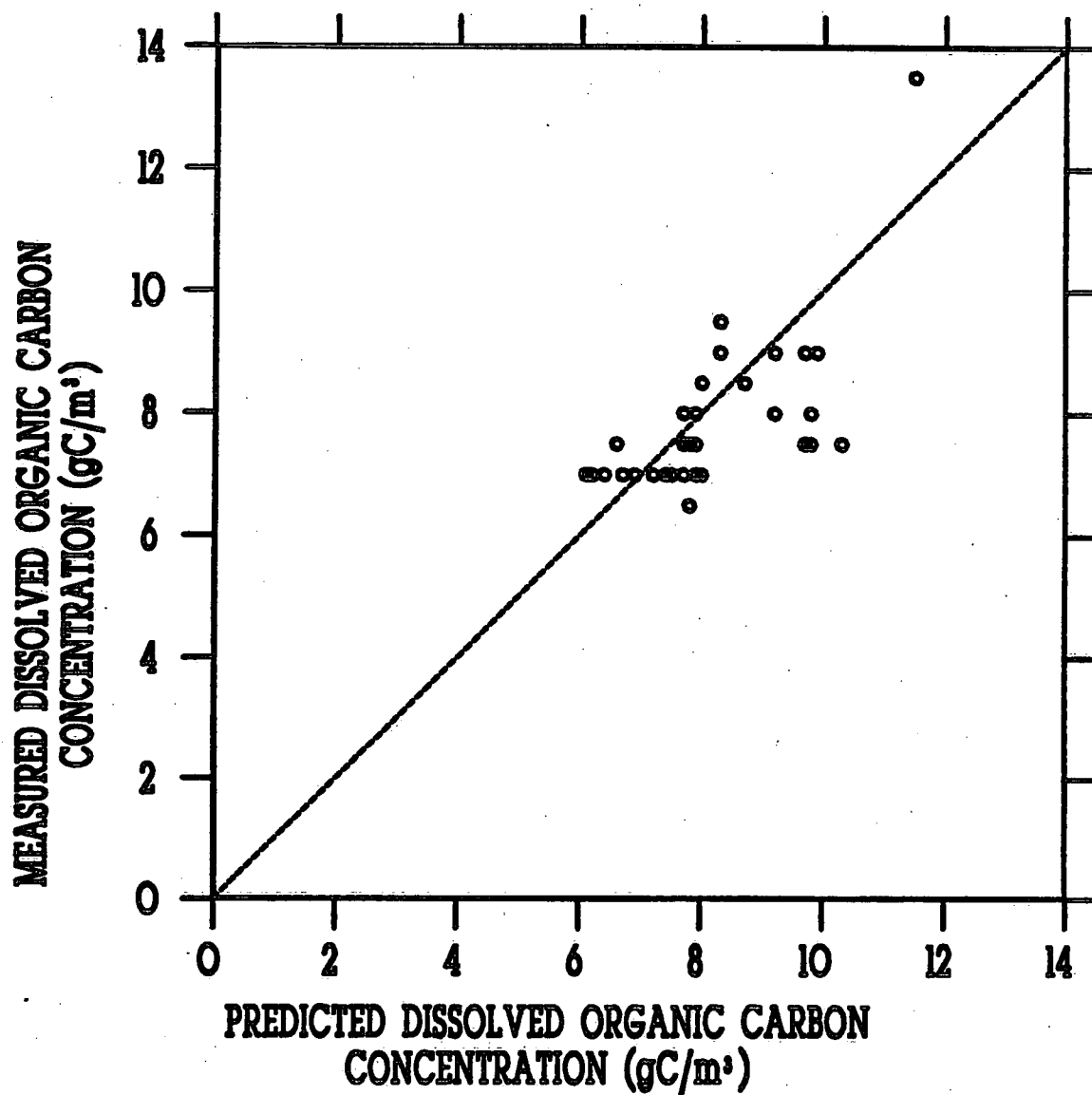


FIGURE 4

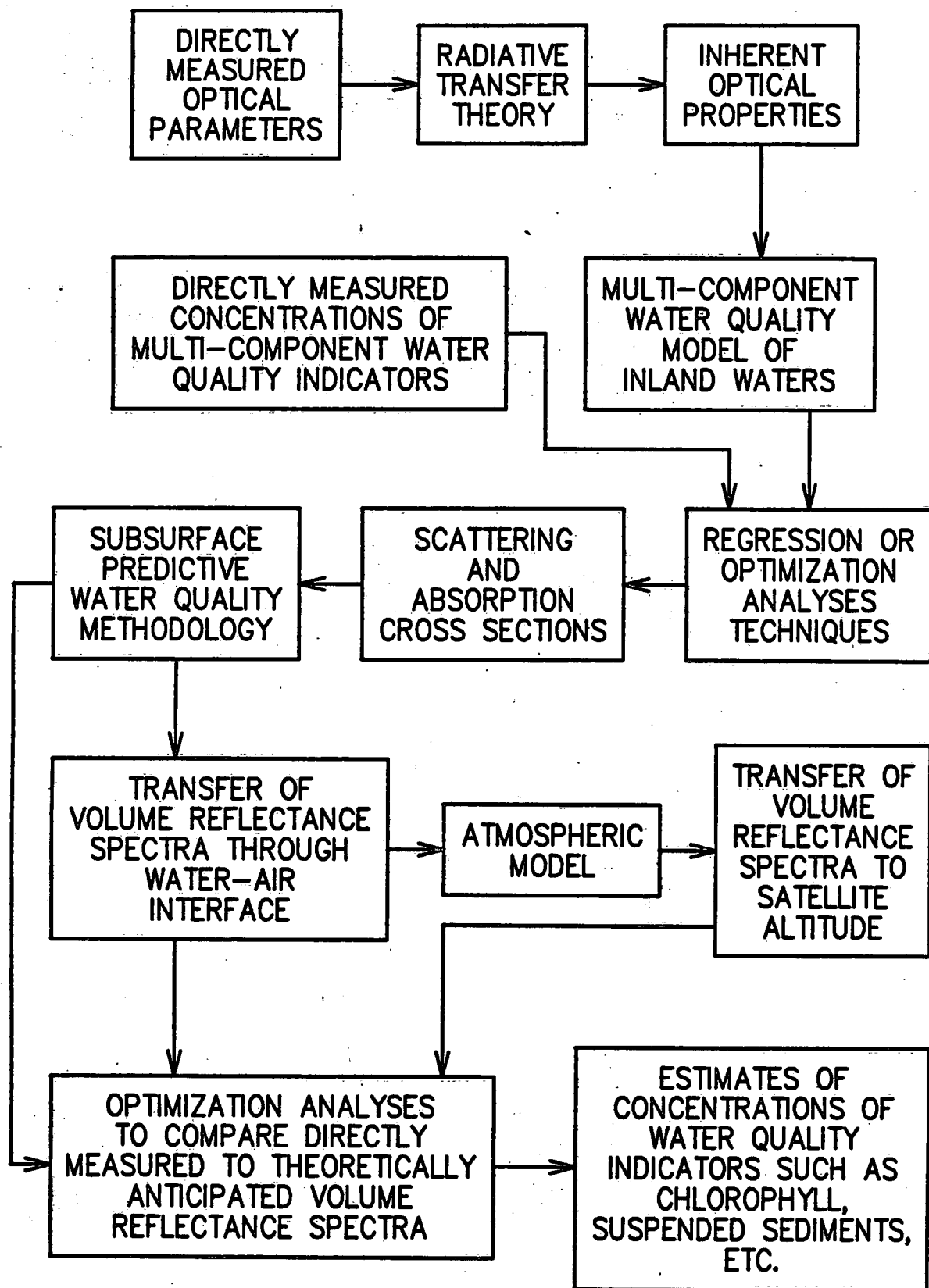


FIGURE 5

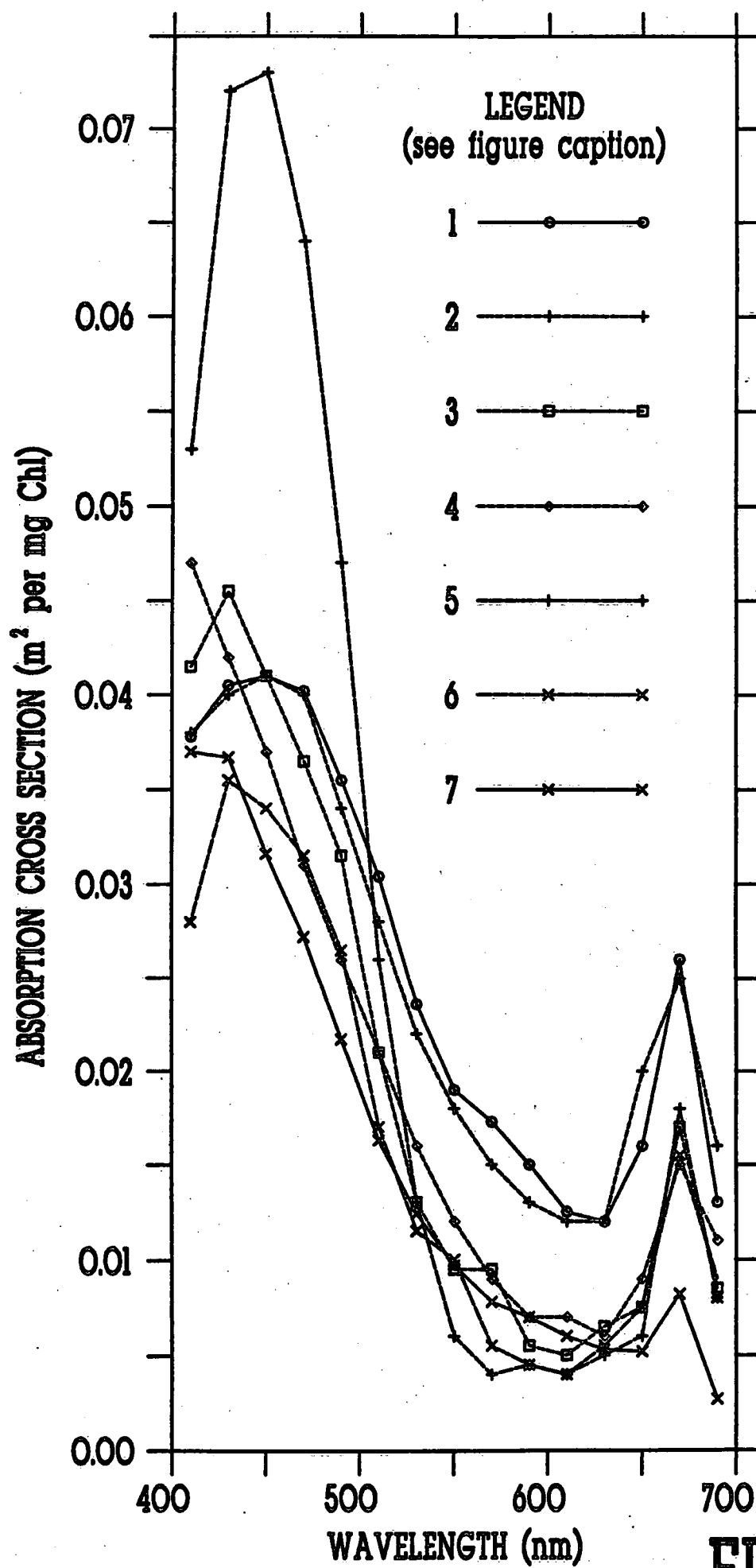
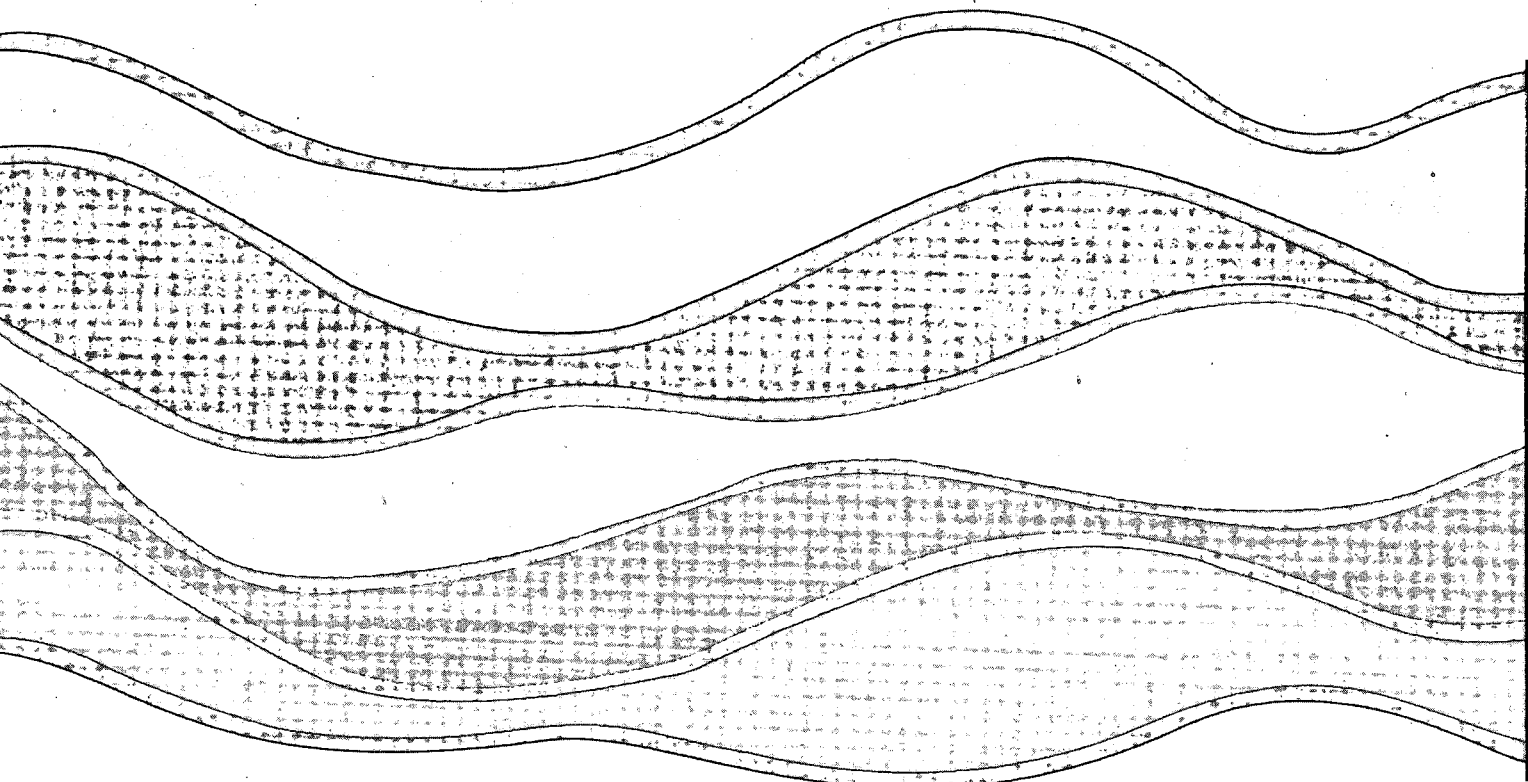


FIGURE 6



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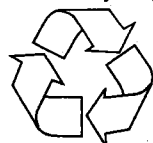
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