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Remote Sensing of Inland Surface Water Quality — Measurements in the Visible Spectrum

By A. A. GITELSON[1]) and G. P. KEYDAN[2])

Abstract: Methods of decoding the diffusively scattered radiation spectra in a visible wavelength range have been investigated. Using remote data, decoding features of optically-active ingredients, have been found, which allow to determine the chlorophyll-a concentration with a standard deviation less than 2.6 mg · m^{-3}, mineral suspended substances concentration will less than 4 mg · l^{-1}, and dissolved organic substances with less than 0.5 mg C · l^{-1}. An equipment for the registration of the upwelling radiation as well as for the express determination of the concentration of phytoplankton chlorophyll-a, suspended mineral substances, and dissolved organic matter have been described.

Zusammenfassung: In der Arbeit wird eine spektrometrische Methode für die Bestimmung optisch-aktiver Wasserinhaltsstoffe (gelöste und suspendierte organische Stoffe, Phytoplankton, Mineralsuspensionen) durch ihre Strahlung im sichtbaren Spektralbereich dargestellt. Beschrieben werden die Apparatur für die Fernsondierung, die angewandten Express-Kontaktmethoden zur Bestimmung der Konzentration von Inhaltsstoffen und die Verfahren zur Datendechiffrierung.

Резюме: В работе рассмотрен спектрометрический метод определения концентраций оптически активных ингредиентов (растворенные и взвешенные органические вещества, фитопланктон, минеральные взвеси) по излучению водных объектов в видимой области спектра. Описана аппаратура для дистанционного зондирования, применяемые в эксперименте экспрессные контактные методы измерения концентраций ингредиентов, способы дешифрирования получаемой информации.

Introduction

The methods and apparatus for remote non-contact sensing of aquatic ecosystem quality indices according to their radiation in the visible spectrum are discussed in this work.

The functional relationship between the spectral brightness coefficient (SBC), which is the measure of radiation upwelling from water and concentrations of

[1]) Анатолий Абрамович Гительсон, заведующий лабораторией Гидрохимического института Госкомгидромета СССР. СССР 344004 Ростов н/Д ул. Калинина 26-а кв. 64.
Prof. Dr. Analoiĭ Abramovich Gitelson, 26ª/5 Uziel Street, Batiam 59463, Israel.

[2]) Галина Петровна Кейдан, старший научный сотрудник Ростовского Государственного университета.

optically active ingredients, is the basis for the method. Our studies of SBC functional relationship and terrigenous and biogenic components of particulate matter [4], [5] revealed the possibility of remote sensing of these most important physico-chemical parameters of the water body from its radiocharacteristics. However, the effect of particulate matter concentration on SBC is less important than the effect of their qualitative composition [1]. SBC is calculated from the ratio [2], [7]:

$$\varrho = 0.14 \frac{\Psi}{\varkappa + \Psi}, \tag{1}$$

where — Ψ is the index of backwards light scattering, $\varkappa$ is the water absorption index. Primary hydraulic optical parameter Ψ and $\varkappa$ are related to the function of particle size distribution, etc. If we take into account that for inland surface waters rather high concentrations of dissolved substances are typical and among them organics possessing quite different absorption spectra and the fact that phytoplankton species composition is rather diverse and variable seasonally, it will be clear that even for a single water body with specific ingredient composition, granulometric composition of suspended substances and phytoplankton species composition, the relationship between SBC and concentrations of optically active ingredients is ambiguous. Only a stable relationship between physico-chemical and radioparameters is the basis of remote sensing of water body quality.

The study of radioparameters of a number of water bodies of the European area of the USSR (the rivers Don, Seversky Donez, Dniepr, Bug, the Tsymlianskoye Reservoir, the Sea of Azov, etc.) and Lake Balaton indicated that for some water surfaces there exists rather definite relationship between the concentrations of suspended substances and SBC. However, these relationships are typical for the given water body or a part of it only in a certain season and are subject to important variations in different hydrological phases, conditions of hydrobiota development, etc. Besides, the results of SBC measurements obtained by the different authors are not readily comparable due to the application of different excellent scatterers and opal glasses for the measurement of downward irradiance, to differences in the characteristics of downwelling and upwelling radiation receiving paths (and, in particular, different angles of sensing) etc. Therefore, it is impossible to derive the concentrations of optically active ingredients from informations about absolute SBC values.

Thus, the development of radioparameters related to SBC invariant to apparatus functions of the register transmissions and allowing to evaluate chemical and biological conditions of water bodies is necessary. In this case the functional relationship between such a radioparameter and physico-chemical parameters of a water body should be stable in time and space. That means that one should have a possibility to extrapolate the functional relationship obtained to different

hydrological phases and phases of hydrobiota conditions to the maximum distances and, in particular, to water bodies differing from those studied.

Such determination of the problem is important both for the application of passive spectrometry for remote sensing of water body's quality and for the development of the data bank of a priori information necessary for the interpretation of satellite multi-zonal visible informations [4], [6].

Thus, the problem is to develop the radiomodel of a water body describing the relationship between radiation features and physico-chemical parameters which may be applied for the description of other water bodies providing the necessary precision of evaluation.

The development of radiomodels of water bodies was carried out on the basis of numerous simultaneous measurements of radiofeatures on the one hand and water chemistry and aquatic biology parameters, on the other.

The Meters of Spectral Brightness Coefficients and Primary Hydraulic Optical Parameters

The instruments for SBC measurement are developed according to different circuits. Some of them detect the signal measured (sky brightness, water surface brightnesses or water surface irradiation) sequentially at the different wave lengths of the band studied, the others detect the signal simultaneously in the different areas of the spectrum. Let us name those based on the first principle the spectrometers of sequential signal detection, the others the spectrometers of simultaneous signal detection. Sequential detection spectrometers allow to obtain the detailed radiation spectra; however, the registration period of each of them is rather long — up to 25—20 seconds (it is related to the period of dispersive element transformation at the given spectral resolution and sensitivity). It is evident that their application is reasonable for the study of the radiation spectra and for the determination of spectral characteristics capable to determine the decoding features of different water body conditions. Simultaneous detection spectrometer usually measures spectral brightnesses and irradiance in several regions of the spectrum (up to 10—12) providing high registration speed — up to 0.1—0.5 s (it is limited by the time of switching of the channels receiving different light fluxes). It is reasonable to apply them in the observation systems to control radiation in several information spectral channels and to estimate optically active ingredient concentrations from them.

We have developed and applied spectrometers with sequential ("Spectr-01") and simultaneous ("Tzvet") signal detection in the field tests.

The meter "Spectr-01" transforms light fluxes proportional to the spectral density of water surface energy brightness (SDEB), SDEB of the sky, and spectral

density of energy irradiance (SDEI) of the water surface to the equivalent electric signals. The period of the measurement of one spectrum is 10 seconds. Registration of the information is conducted with XY-recorder in the "brightness — wave length" or "SBC — wave length" plot and in the automatic data storage of APRD type [11]. Analogous signals in APRD are transformed to the digital code according to frequency marks formed in the spectrometer or with the automatic sampling in the storage of the discretization step. Brightness or irradiance spectra of SBC are presented by the representative data file in the storage. Information is transmitted from the data storage to the punch PL-150 or through special interfaces to the computer.

The measuring unit installed in the place convenient to obtain on-side information — on the bow of a ship, helicopter's frame, air-plane's cabin, etc. — is connected to the manual control desk with multiple-conductor cable.

The spectrometer with simultaneous signal detection "Tzvet" is intended for the measurement of brightness spectra and irradiance of the water surface in nine fixed areas of the spectrum. The instrument transforms light fluxes proportional to SDEB and SDEI of the water surface and ADEB of the sky to equivalent electric signals as well. The period of one cycle of measurements may vary from 0.1 to 2 s. In this case the meter may function in two modes: continuous reading of the information from one of the channels, for instance, water brightness, and successive scanning of the channels of water SDEB and SDEI, SDEB of the sky, and test mode through equal time intervals.

The spectrometers of sequential and simultaneous signal detection are characterized by the following parameters:
spectral band from 400 to 750 nm;
spectral resulution:

- at sequential detection 1 nm;
- at simultaneous detection of 9 channels 5—8 nm width;
- band of spectral irradiance measurement from 10^7 to 10^9 W/m^3;
- measurement band of sky brightness from $3 \cdot 10^5$ to $3 \cdot 10^8$ W/(m^3 · sr);
- measurement band of water brightness from 10^5 to 10^7 W/(m^3 · sr);

error of brightness and irradiance measurement

- relative 5%;
- absolute 15%.

Portable spectrometer, nephelometer and spectrofluorimeter were developed to carry out simultaneous quick-screening and spectrometric measurements (abord or in the helicopters cabin) of attenuation and scattering index and water fluorescence. The spectrometer was intended to measure the water attenuation index and to determine the turbidity-concentration of suspended substances in the band from 0.1 to 50 mg/l. The length of optical glass fibre of the spectrophotometer is

20 m which allows to locate the sensor 10 m from the measuring unit and to carry out quick-screening in situ measurements of the water attenuation index and the turbidity in the wave band from 420 to 750 nm.

The nephelometer is intended for measuring water scattering index at the 90° angle. Concentration of suspended substances in the bands from 0 to 15 mg/l and from 0 to 150 mg/l according to kaoline was estimated from the value of the scattering index.

Calibration of the monochromator according to the wave length is conducted either automatically or manually. The fluorescence voltages from the amplifer output of the measuring channel and the voltage, which is proportional to the wave length of the monochromator adjustment, are the input to the recorder. For instrument calibration the measuring cell is replaced by the fluorent one with the known level of fluorescence at the given wave length. Variation and fine adjustment of the fluorimeter is carried out with the installation of neutral light filters to the acting channel (stepwise) and rotation of polarization filters and a diaphragm in the basic channel (smoothly).

The resolution of the instrument according to the wave length is at least 2.0 nm.

Measurement Methods and Primary Results

The main object of the experimental investigation is the study of quantitative relationship between SBC (spectral brightness coefficient) measured onboard the helicopter or the ship, and physico-chemical parameters of water bodies determining their radiation in the visible spectrum region.

SBC was measured directly over the water surface with the instrument onboard the ship or the helicopter flying at low altitude. SBC is calculated by the equation (1) to (3):

$$\varrho(\lambda) = \frac{B(\lambda) - rB_s(\lambda)}{B_0(\lambda)} \tag{2}$$

where $B(\lambda)$ — brightness of radiation upwelling from water;
$B_s(\lambda)$ — sky brightness in the zenith;
$B_0(\lambda)$ — ideal scattering brightness equal to $E_0\pi$,
where E_0 — downward water irradiance;
r — FRESNEL reflectance coefficient.

At the observation in nadir the angle of reflected ray incidence on the surface does not deviate considerably from 90°. Because FRESNEL reflectance coefficient

in the region of such angles of incidence does not depend importantly on the angle [1] it may be assumed to be equal to normal reflectance coefficient

$$r_1 = \frac{(n - 1)^2}{(n + 1)^2} = 0.02 \tag{3}$$

where n denotes the water refraction index.

To test the stability of the functional relationships determined, quite different water bodies and streams such as the Don, Taganrog Bay of the Sea of Azov. Seversky Donez and Lake Balaton were chosen. The rivers Don and Seversky Donez differ in the type of predominant suspended substances (in the Don — clayish mineral suspensions, in the Seversky Donez — humic ones in colloidal and suspended forms), anthropogenic load, granulometric composition and refraction indices of suspended substances. The Sea of Azov and Lake Balaton differ from each other considerably. Thus, we got a possibility to reveal functional relationships between radioparameters and physico-chemical ones for water bodies and streams with different hydrochemical regimes and trophicity level.

In 1983 measurements of more than 150 relationships between SBC and wave length were carried out at the three water bodies (the Sea of Azov, the rivers Don and Seversky Donez). The measurements indicated that there were 33 quasi-homogeneous zones according SBC, where the chlorophyll-a concentration of phytoplankton, its volume and biomass and the concentration of suspended mineral substances were estimated analytically. Besides, surface wind, water temperature and relative SECCHI disk transparency were measured. SBC was measured with the spectrometer "Spectr-01" described above.

To study the stability of the radiation-concentration relationships of 1983 and the possibility of their extrapolation in time, SBC were measured simultaneously with the analytical determination of phytoplankton chlorophyll-a and suspended mineral substances in 1984 at the same water bodies at 93 observation points in 44 quasi-homogeneous regions according to SBC. Besides, the water attenuation index was measured by spectrophotometer. The spectrometers "Spectr-01" and "Tzvet" were used for SBC measurement.

In 1985 at the river Don and the Sea of Azov and Lake Balaton SBC measurements with the spectrometers "Spectr-01", "Tzvet", of fluorescence of the samples and their filtrates in the wave band from 600 to 900 nm, water scattering and attenuation index were carried out at more than 200 observation points. Besides, the concentrations of phytoplankton chlorophyll-a, suspended mineral substances, humic and fulvic acids were estimated analytically. At Lake Balaton in addition to the above instruments the TURNER mod. 10 fluorimeter-nephelometer was used. Measurements of the water fluorescence in the red region of the spectrum (at the waves longer than 600 nm) and of the water scattering index at 90° were carried out in the regime of water pumping through the measuring cell.

In 1986 two sets of experiments at the rivers Don, Seversky Donez and the Tsymlianskoye Reservoir (more than 150 observation points) and Lake Balaton (50 observation points) were carried out. All the above instruments were used in the experiments. Probably the most complete (of those known) apparatus set allowing simultaneous measurements of SBC and precise quick screening of the concentrations of phytoplankton chlorophyll-a, suspended substances, and water optical parameters was used in the experiments. This allowed to compare physico-chemical parameters and radiocharacteristics of the water bodies and to reveal decoding parameters of optically active ingredients on the basis of spectrometric information.

Quick Screening of Organic and Mineral Substances

In 1983 and 1984 the concentrations of phytoplankton chlorophyll-a and mineral substances were estimated analytically. Thus, due to considerable labor consumption and low efficiency of analytical methods, the hydrobiological and hydrochemical information file was not sufficient to carry out correct factor analysis and to detect correlations between biological and chemical parameters and radioparameters. Besides, while measuring radioparameters simultaneously with chemical and biological parameters of the water bodies, there appears a necessity to determine the sufficiency of the information for processing, dynamic range of ingredient concentration variation, etc. in the actual time scale. The data of analytical determinations obtained, at the best, in several hours after sampling do not allow to do this. It must also be noted that the analytical determination of phytoplankton chlorophyll-a concentration and the concentrations of suspended substances is a complicated multi-factor experiment and each factor is not always stabilizable in this experiment. It is especially evident while determining low concentrations of chlorophyll-a (C_{chl}) and suspended mineral substances (C_{sus}) — a whole set of procedures in the estimation of ingredient concentrations cannot be reproduced with sufficiently unimportant errors.

It is also very important to screen the concentrations of dissolved organic substances (DOS) quickly. DOS is an optically active ingredient determining mainly spectral features of water radiation in the visible spectrum. The study of this effect cannot be conducted without correct quick screening of C_{dos}. All this is necessary for the development and test of quick-screening methods for the measurement of C_{chl} and C_{dos}.

To measure the concentrations of chlorophyll-a and dissolved organic substances we used the fluorimetric method in which water sample fluorescence at the definite wave length measures C_{chl} and C_{dos}. The length of the excitation waves is 400 to 500 nm.

The decoding feature of chlorophyll-a on fluorimetric information is evident — water fluorescence at the wave $\lambda = 680$ nm or integral radiation in the wave region more than 600 nm.

It is more difficult to choose the decoding feature for DOS. The relationship between DOS fluorescence and wave length (λ) is the exponential descreasing with λ growth. Maximum DOS excitation is observed in UV and blue spectrum regions. However, since the wave length band for the determination of C_{chl} is predetermined, it is reasonable to define a possibility to measure C_{dos} according to fluorescence in the red spectrum region. This would allow to use one instrument to measure concentrations of both ingredients.

To determine precise characteristics of the procedure of C_{chl} fluorimetric estimation, in vivo measurements of water fluorescence with spectrofluorimeter in the wave band from 630 to 750 nm were carried out. Simultaneously, C_{chl} in the water samples is determined by extraction and photometry of the extract [9]. The analyses were carried out 6—8 hours after sampling; the samples were stored in semi-transparent containers at a temperature of 18—20 °C. Just before the analyses, water sample fluorescence was once more estimated in a laboratory. Simultaneously with field and laboratory measurements by the spectrofluorimeter sample, fluorescence measurements in the wave band from 600 to 750 nm were conducted with the fluorimeter TURNER mod. 10.

The regression equations of the relationship between C_{chl} and luminescence intensity at the wave $\lambda = 680$ nm are the following:

$$C_{chl} = 4.24 + 4.5U_{680}^{lab} \text{ mg} \cdot \text{m}^{-3} \tag{4}$$

with correlation coefficient $R = 0.97$, factor $P = R^2(n - k - 1)/k(1 - R^2)$ exceeding 520 (n — number of measurements, k — number on independent variables):

$$C_{chl} = 4.45 + 3.5U_{680}^{in\ situ} \text{ mg} \cdot \text{m}^{-3} \tag{5}$$

with $R = 0.96$, $F = 311$ for the in vivo/in situ measurements.

Both equations are valid in the chlorophyll-a concentration range from 3 to 100 mg $\cdot$ m^{-3}.

In the same experiments the possibility of estimation C_{chl} from water fluorescence in the wave band from 600 to 750 nm, measured with the fluorimeter TURNER mod. 10, was defined. Regression equations of the relationship between these characteristics are the following:

$$U_{600-750}^{in\ situ} = -16.6 + 16.1C_{chl} \tag{6}$$

with $R = 0.944$, $F = 250$;

$$U_{600-750}^{lab} = -3.07 + 2.86C_{chl} \tag{7}$$

with $R = 0.96$, $F = 308$.

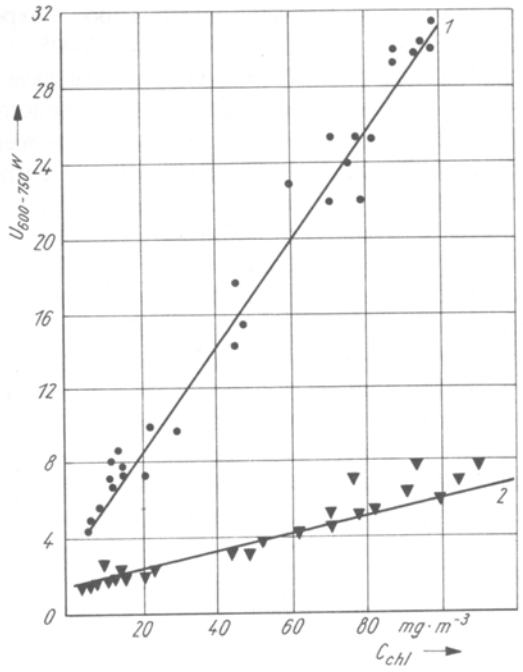

Fig. 1. Relationship between water luminescence signal measured in situ (curve 1) and in laboratory conditions (curve 2) in the wave band 600–750 nm with Turner fluorimeter and phytoplankton chlorophyll "a" concentration.

Fig. 1, presenting the relationships $U_{600-750}(C_{chl})$, indicates that fluorescence intensity in the wave band from 600 to 750 nm (as well as the wave $\lambda = 680$ nm) is higher in the in situ measurements than water fluorescence intensity measured 6—8 hours after sampling. Leaving along the reasons for this we should note the important point: there is a stable relationship between fluorescence signals and phytoplankton chlorophyll-a concentration. Functional relationships obtained in situ and in the laboratory prove the possibility to measure C_{chl} from water fluorescence in the red spectrum region. It should be noted that the data of fluorescence measurement at one wave length ($\lambda = 680$ nm) obtained with the spectrofluorimeter and in the wave band (600—750 nm) obtained with the fluorimeter TURNER mod. 10 correlate.

$$U_{680} = -0.034 + 0.826 U_{600-750} \tag{8}$$

with $R = 0.99$, $F = 5200$.

The sensitivity of the method was determined in model experiments. Phytoplankton chlorophyll-a concentration in the vessel was 0.005—0.01 mg · m^{-3}. In this case the maximum of the fluorescence spectrum at the wave $\lambda = 680$ nm was quite distinct. Signal/noise ratio was at least 10. This concentration value is probably to be considered as the threshold sensitivity of the method.

The above method of C_{chl} concentration estimation is correct when phytoplankton fluorescence considerably exceeds fluorescence signal of DOS at the wave $\lambda = 680$ nm (when we use spectrofluorimeter) and in the wave band (when we use zonal fluorimeter like TURNER mod. 10). At low C_{chl} concentrations and high C_{sus} the "zonal" methods are actually insensitive to C_{chl}, since the fluorescence signal is determined mainly by C_{dos}. Thus, to estimate C_{chl} correctly using fluorimeters it is necessary to measure both, the water sample and its filtrate fluorescence. The difference between the fluorescence signals is the measure of C_{chl}.

Using spectrofluorimeters it is possible to estimate C_{chl} without filtrate fluorescence measurement. The method of the determination is based on the known principle of variation of the signal of DOS fluorescence with the wave length. This relationship is assumed to be the following:

$$U_{\lambda_i} = \exp(a\Delta\lambda + kC_{dos}) \tag{9}$$

where C_{dos} — fluorescent dissolved substance concentration;
a — coefficient determined by the quantum output of fluorescence;
k — coefficient determined by the apparatus function of the instrument;
$\Delta\lambda = \lambda_i - \Lambda$
λ_i — current value of the wave length;
Λ — wave length of U value measurement.

Coefficient a appeared to be constant for each of the water bodies studied. Thus, for Lake Ladoga it is 10^{-2}, for Lake Balaton — $2 \cdot 10^{-2}$.

The algorithm of the in situ determination of the C_{chl} concentration is evident. The fluorescence signal is estimated at the wave where chlorophyll-a fluorescence contribution is negligible, for example at the waves from 560 nm to 630 nm. DOS fluorescence stress at the wave 680 nm is estimated from the formula (9). The difference between the fluorescence signal of the water sample and the fluorescence of DOS (in the filtrate of the sample) at the wave length 680 nm determines C_{chl}. Spectrometer and nephelometer are used for the estimation of suspended mineral substance concentrations. For all the water bodies studied, the correlation coefficient of the scattering index at 90° and C_{sus} was at least 0.9 with the factor F exceeding 500. This proves sufficient reliability of C_{sus} evaluations on the basis of the water scattering index at 90°.

Composition of the Data Base

The results of the measurements of water body spectral brightnesses, sample and filtrate fluorescence, water attenuation and scattering indexes as well as hydrochemical and hydrobiological parameters were introduced into the computer from the information storage. For each experiment a data file was formed at the magnetic carrier. The number of units in it corresponded to the number of zones homogeneous according to SBC at the water body. The following information was introduced to every unit:

- spectral brightness of radiation upwelling from water at 18 waves in the band from 440 to 780 nm;
- spectral brightness of radiation upwelling from the ideal scatterer at 18 waves;
- water attenuation index at 7 waves in the band from 440 to 680 nm;
- water scattering index at 90°;
- spectral brightness of radiation upwelling from water in 9 spectrum zones of the wave band from 440 to 750 nm;
- spectral brightness of the sky in zenith in 9 spectrum zones;
- downwelling water radiation in 9 spectrum zones;
- water fluorescence signal intensity in the wave band from 630 to 780 nm;
- intensity of the signal of water sample filtrate fluorescence in the wave band from 630 to 780 nm;
- intensity of standard fluorescence signal;
- phytoplankton chlorophyll-a concentration;
- concentration of suspended mineral substance;
- concentration of fulvic acids;
- biomass and volume of phytoplankton;
- concentration of humic acids;
- weather factors;
- water temperature;
- water surface condition.

Analysis of the Results

Factor analysis of the obtained brightness spectra and SBC indicate that the spectral brightness coefficient in the wave band from 440 to 780 nm is determined mainly by three factors. One of them is maximum in the red spectrum region (at the waves from 700 to 740 nm); the third — in the blue one (at the waves from 480 to 440 nm). The first of these factors, let us name it "water body biota condition", is related to phytoplankton chlorophyll-a concentration, productivity, its volume and biomass. The second factor is related mainly to the concentrations of particles scattering light in water. It is determined by the concentration of

mineral and organic substances. The third factor is related to DOS concentration in water.

It is evident that none of the above factors is fully determined by the concentration of one of the ingredients measured. However, using the methods of the optimization of F-factor and standard error of the evaluation of any ingredient from SBC $\left(S_c = \left[\sum_{k-1}^{n} (\bar{c} - c_i)^2/(n-k-1)\right]^{1/2}\right)$, we managed to define the wave band where SBC is as firmly related to the concentrations of phytoplankton chlorophyll-a and to the suspended mineral substances as possible [4], [5]. The regression equations obtained allowed to evaluate C_{chl} from SBC values in the red spectrum region and C_{sus} — in the green one. The decoding features based on the relationship between ingredient concentrations and SBC values in the informative spectrum areas appeared to be quite useful for understanding the physical processes of water body radiation formation. The radiomodels developed on their basis are the first approximation of the solution of the inverse problem — the estimation of the concentrations of optically active ingredients from the water body radiation in the visible spectrum. Further investigations indicated that empirical models of [4], [5], [8] type, though reflecting basic radiation-concentration relationships, are not stable from year to year and are not valid for different water bodies. The experiments carried out in 1984 (at the water bodies of the 1983 investigations) indicated important growth of the standard errors of

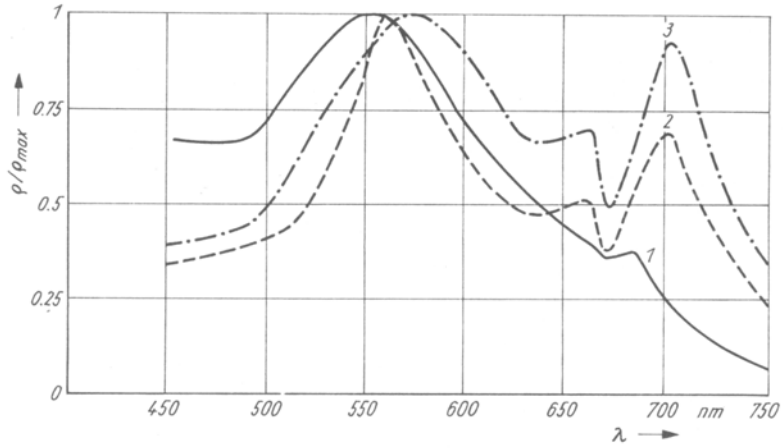

Fig. 2. Relationship between SBC (ϱ) and radiation wave length (λ) with
1 — C_{chl} = 5 mg m^{-3}, C_{sus} = 5 g m^{-3};
2 — C_{chl} = 64 mg m^{-3}, C_{sus} = 31 g m^{-3};
3 — C_{chl} = 99 mg m^{-3}, C_{sus} = 40 g m^{-3}.

the C_{chl} and C_{sus} evaluation compared to those estimated from the 1983 data [4]. C_{chl} and C_{sus} grew to the values 7 mg · m^{-3} and 9 mg/l, correspondingly.

Therefore, the development of radiomodels is stimulated applicable to different water bodies (within one class) in different years hydrological phases etc. In this case there must be invariance both to the conditions and remote sensing equipment and relative to the factors which are not taken into account yet but determine, to a certain extent, to water body radiation: phytoplankton species composition, concentrations of humic and fulvic acids, granulometric composition of suspended substances, etc. The decoding feature on spectrometric information should, probably, be presented by the SBC ratio at the wave where it is most sensitive to the concentration of the ingredient measured, to the parameter mostly determining water body radiation in the visible spectrum region — water scattering and absorption.

The relationship $\varrho(\lambda)$ (Fig. 2) is characterized by a number of spectral features;

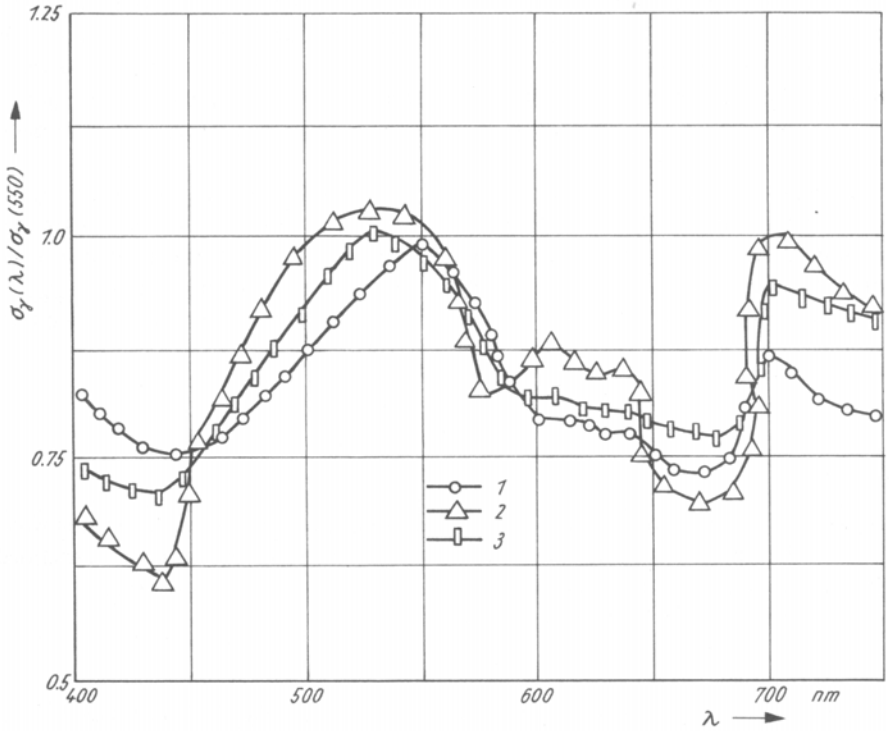

Fig. 3. Spectral relationships between water scattering index at 90° and algamonocultures; 1 — Anabaena; 2 — Chlorella; 3 — Selenastrum.

it is reasonable to relate them to decoding feature components. In the wave band 550—570 nm SBC maximum is observed mainly related to the light scattering at suspended particles. In the wave band 660—670 nm we observe a minimum related to the maximum of the chlorophyll-a absorption index in this region. At the wave lengths from 685 to 700 nm we observe maximum radiation growing with chlorophyll-a concentration increase. Besides, at high concentrations of chlorophyll-a we observe 2 local extremes of radiation — minimum in the wave band 620—640 nm and maximum at the wave 650 nm.

To reveal the reasons stimulating radiation increase at the wave lengths 685 to 700 nm, we carried out a set of laboratory experiments for the determination of the scattering index at 90° and 135° of water with monocultures of phytoplankton of different species composition (Fig. 3). The spectra of water scattering index with all monocultures clearly show four spectral features — minimum at the waves 420—440 nm, maximum at the waves 550—570 nm, minimum in the band 660 to 670 nm and sharp increase of scattering index at the waves longer than 700 nm. The relationships of water scattering index at 135° are similar. At high chlorophyll-a concentrations the spectra of the scattering index are actually similar to the relationships $\varrho(\lambda)$. It must be noted that scattering at phytoplankton particles and in the wave band 540—580 nm is important. That means that the global maximum in SBC spectrum should be related to the light scattering both at mineral and organic suspended particles.

Intensive scattering at phytoplankton particles in the red spectrum region characterized by maximum radiation at the wave 700 nm may be one of the decoding feature components on spectrometric information for phytoplankton chlorophyll-a determination. SBC limitation in this spectrum region — ϱ_{100} is reasonable either for all radiation upwelling from water in the visible spectrum region

$$\int_{\lambda_{\min}}^{\lambda_{\max}} \varrho(\lambda)\,\mathrm{d}\lambda$$

or for SBC corresponding to global maximum at the wave 560 nm. At this wave SBC is determined both as the concentration of mineral and organic suspended substances, i. e. it is, to a certain extent, a measure of water scattering.

A whole set of decoding features was tested:

$$\varrho_i/\varrho_{\max}, \quad \varrho_i \Big/ \int_{\Delta\lambda} \varrho(\lambda)\,\mathrm{d}\lambda, \quad \varrho_{700}/\varrho_{675}, \quad (\varrho_{700}-\varrho_{675})/(\varrho_{700}+\varrho_{675}),$$
$$\varrho_{700} \Big/ \int_{\Delta\lambda} \varrho(\lambda)\,\mathrm{d}\lambda, \quad (\varrho_{700}-\varrho_{675}) \Big/ \int_{\Delta\lambda} \varrho(\lambda)\,\mathrm{d}\lambda \tag{10}$$

TABLE 1

Radio parameters	$\frac{\varrho_{700}}{\varrho_{675}}$	$\frac{\varrho_{700}-\varrho_{675}}{\int_{\Delta\lambda}\varrho(\lambda)\,d\lambda}$	$\frac{\varrho_{700}}{\varrho_{560}}$	$\frac{\varrho_{700}}{\int_{\Delta\lambda}\varrho(\lambda)\,d\lambda}$
R, rel. units	—0.899	—0.867	0.91	0.72
S, mg m^{-3}	3.52	3.88	3.44	5.56
F, rel, units	101.2	79.20	107.3	26.2

The i^{th} wave length was selected with methods for the optimization of the standard error of evaluation of the concentrations C_{chl} and C_{sus} and F — the factor of the relationship between these concentrations and each of the radioparameters (10). Maximum values of the coefficient of correlation between ϱ_i/ϱ_{max} and C_{chl} and ϱ_i/ϱ_{max} and C_{sus} are sufficiently diverse in the band. The optimal wave length for C_{chl} determination corresponds to the wave 700 nm and C_{sus} —520 nm.

Table 1 includes statistical characteristics of the C_{chl} relation with different radioparameters (from 1983 and 1984 data). It is evident that the most optimal parameters for the C_{chl} evaluation are

$$\varrho_{700}/\varrho_{560}, \quad \varrho_{700}/\varrho_{675}, \quad (\varrho_{700}-\varrho_{675})\Big/\int_{\Delta\lambda}\varrho(\lambda)\,d\lambda \tag{11}$$

Correlation analysis of the data of 1983—84 experiments provided the following correlation equations of the relationships between the chlorophyll-a concentration and radioparameters:

$$C_{chl} = -22.8 + 66(\varrho_{700}/\varrho_{560})\ \text{mg}\cdot\text{m}^{-3} \tag{12}$$

with $R = 0.91$, $F = 107$, $S_{chl} = 3.4\ \text{mg}\cdot\text{m}^{-3}$,

$$C_{chl} = 66.1(\varrho_{700}/\varrho_{560})^{2.8}\ \text{mg}\cdot\text{m}^{-3} \tag{13}$$

with $R = 0.88$, $F = 85$, $S_{chl} = 3.6\ \text{mg}\cdot\text{m}^{-3}$,

$$C_{chl} = 38.0 - 82.5\,\frac{|\varrho_{700}-\varrho_{560}|}{\varrho_{700}-\varrho_{560}}\ \text{mg}\cdot\text{m}^{-3} \tag{14}$$

with $R = 0.9$, $F = 101$, $S_{chl} = 3.52\ \text{mg}\cdot\text{m}^{-3}$,

$$C_{chl} = 1.82\left(\frac{\varrho_{560}-\varrho_{700}}{\varrho_{560}+\varrho_{700}}\right)^{-1.48}\ \text{mg}\cdot\text{m}^{-3} \tag{15}$$

with $R = 0.84$, $F = 62$, $S_{chl} = 3.8\ \text{mg}\cdot\text{m}^{-3}$.

Here R denotes the correlation coefficient, S the standard deviation, n the number of measurements, k the number of independent parameters and

$$F = \frac{R^2(n - k - 1)}{(1 - R^2)\,k}.$$

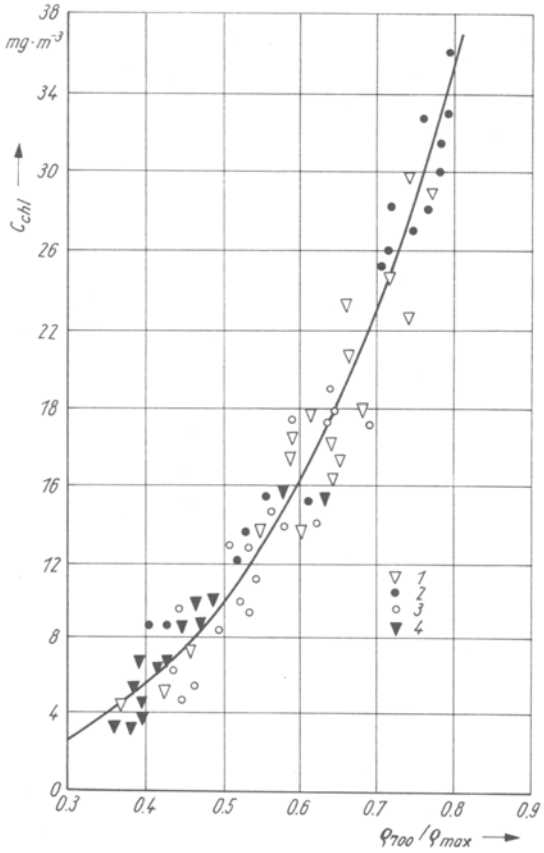

Fig. 4. Relationship between the concentrations of phytoplankton chlorophyll "a" (C_{chl}) and $\varrho(700)/\varrho(560)$ ratio obtained from the data for:

1 — the Don and Sea of Azov (1983);
2 — the Seversky Donetz (1984);
3 — the Don and the Sea of Azov (1984);
4 — the Seversky Donetz (1983).

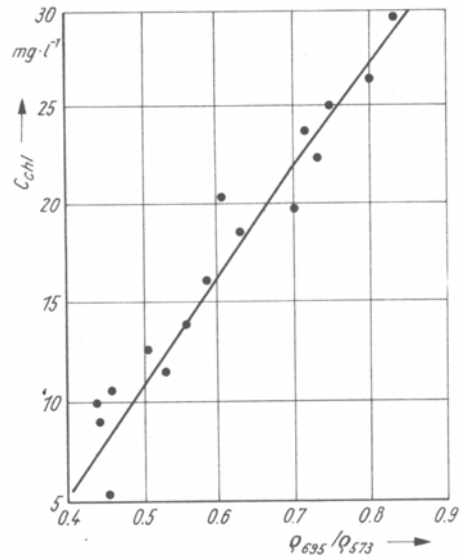

Fig. 5. Relationship between phytoplankton chlorophyll "a" concentration (C_{chl}) and $\varrho(695)/\varrho(573)$ ratio obtained with spectrometer with simultaneous signal detection.

Fig. 4 presents the relationship between chlorophyll-a concentrations measured analytically and $\varrho_{700}/\varrho_{560}$ ratio. Fig. 5 demonstrates the relationship of C_{chl} with $\varrho_{695}/\varrho_{573}$ ratio obtained from the zonal spectrometer data following:

$$C_{chl} = 13.1 + 56.6(\varrho_{695}/\varrho_{573})\ \text{mg} \cdot \text{m}^{-3} \tag{16}$$

with $R = 0.9$, $F = 58$, $S_{chl} = 3.2\ \text{mg} \cdot \text{m}^{-3}$.

Comparison with equation (12) indicates the sufficient invariance of the obtained radioparameter ϱ_i/ϱ_{max} to the apparatus function of the instrument. Differences in the coefficients of the equations (12) and (16) mainly result from the fact that in equation (16) C_{chl} is determined by the SBC ratio in the frequency band 15 to 20 nm, while by equation (12) in the band less than 1 nm.

The selection of the bands in the 9-channel spectrometer is hardly optimal, since the wave length $\lambda = 573$ nm is shifted relative to the maximum of the spectrum $\varrho(\lambda)$.

The obtained models (12)—(16) describe relationships between radiation parameters and hydrochemical and hydrobiological indices for quite different water bodies and streams (the Sea of Azov, the rivers Don and Seversky Donez) in different years, hydrological phases and phases of hydrobiota growth at chlorophyll-a concentration from 1.3 to 40 $\text{mg} \cdot \text{m}^{-3}$ and variations in the concentra-

tions of mineral and suspended substances from 8 to 35 mg $\cdot$ l^{-1}. For each of the water bodies C_{chl} evaluations according to SBC are more precise: the standard value of the error does not exceed 1.5 mg $\cdot$ m^{-3}.

To evaluate concentrations of suspended mineral substances the following decoding features were used:

$$(\varrho_{560} - \varrho_{520})/(\varrho_{560} + \varrho_{520}) \quad \text{and} \quad \varrho_{520}/\varrho_{560} \tag{17}$$

Regression equations of C_{sus} relationship with this parameters for the rivers Don, Seversky Donez and the Sea of Azov from 1983—84 data are the following:

$$C_{sus} = 0.36(\varrho_{520}/\varrho_{560})^{-1.03} \text{ g} \cdot \text{m}^{-3} \tag{18}$$

with $R = 0.76$, $F = 30$, $S_{sus} = 4.5$ mg $\cdot$ l^{-1},

$$C_{sus} = 1.12 - 0.85(\varrho_{520}/\varrho_{560}) \text{ g} \cdot \text{m}^{-3} \tag{19}$$

with $R = 0.73$, $F = 25$, $S_{sus} = 4.8$ mg $\cdot$ l^{-1},

$$C_{sus} = 0.31 + 1.21 \frac{\varrho_{560} - \varrho_{520}}{\varrho_{560} + \varrho_{520}} \text{ g} \cdot \text{m}^{-3} \tag{20}$$

with $R = 0.74$, $F = 27$, $S_{sus} = 4.6$ mg $\cdot$ l^{-1},

$$C_{sus} = \left(\frac{\varrho_{560} - \varrho_{520}}{\varrho_{560} + \varrho_{520}}\right)^{0.36} \text{mg} \cdot \text{m}^{-3} \tag{21}$$

with $R = 0.71$, $F = 23$, $S_{sus} = 5.0$ mg $\cdot$ l^{-1}.

Fig. 6 presents the relationship between the concentrations C_{sus}, measured analytically and the ratio $\frac{\varrho_{560} - \varrho_{520}}{\varrho_{560} + \varrho_{520}}$ from 1983—84 data.

In 1985 and 1986 the radiomodels developed were tested at the Sea of Azov and the Don and Lake Balaton as well.

In the area of Arabatsk Bay, the Sea of Azov, chlorophyll-a concentrations were 1—3 mg $\cdot$ m^{-3}, the concentrations C_{sus} from 3 to 7 mg $\cdot$ l^{-1}. The concentrations C_{chl} measured from ϱ_{700} and ϱ_{560} values (equation 13) were similar to those measured with spectrofluorimeter characterized by mean square deviation not exceeding 1.5 mg $\cdot$ m^{-3}. Concentrations of suspended substances estimated from ϱ_{560} and ϱ_{520} values (equation 18) were similar to those measured with nephelometer characterized by a mean square deviation not exceeding 2.5 mg $\cdot$ l^{-1}. C_{sus} values from 1 to 3 mg $\cdot$ l^{-1} (according to caoline) were probably close to the sensitivity threshold of spectrometric methods when they were applied aboard. Experiments carried out at Lake Balaton in 1985—86 allowed to try the obtained radiomodels at the water body with chlorophyll-a concentrations varying 20 times within the area of the lake. In September 1985, C_{chl} varied across the lake area

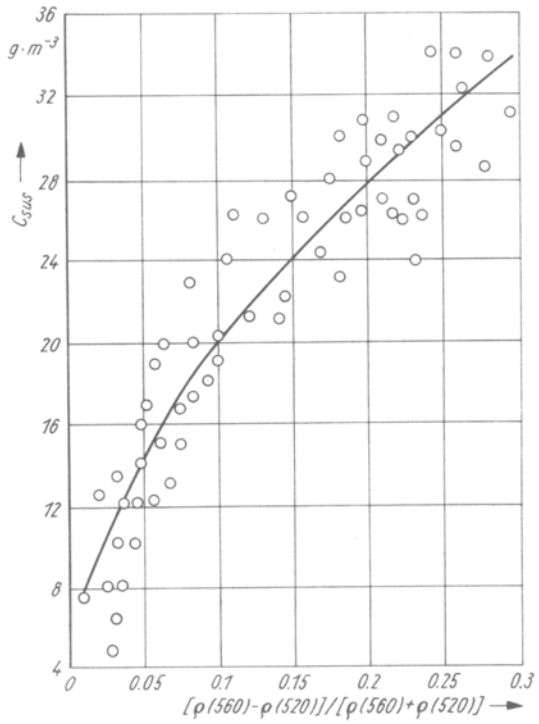

Fig. 6. Relationship between the concentrations of mineral suspended substances (C_{sus}) and $(\varrho_{560} - \varrho_{520})/(\varrho_{560} + \varrho_{520})$ ratio, obtained at the rivers Don and Seversky Donetz 1983–84.

from 5 to 100 mg · m^{-3}, and C_{sus} — from 5 to 40 mg · l^{-1}; in July 1986 C_{chl} varied from 19.5 to 100 mg · m^{-3} with variations in the concentration of suspended mineral substances from 23 to 48 mg · l^{-1}. Spectrometric data and results of C_{chl}, C_{sus} and C_{dos} measurement were compared and processed according to the above methods.

The analysis indicated that $\varrho_{700}/\varrho_{560}$ ratio is the optimal radioparameter for the estimation of chlorophyll-a concentration in Lake Balaton.

Regression equations of the relationship between C_{chl} and this parameter are the following:

$$C_{chl} = -52 + 166.5(\varrho_{700}/\varrho_{560}) \text{ mg} \cdot \text{m}^{-3} \tag{22}$$

with $R^2 = 0.915$, $F = 1548$, $n = 103$,

$$C_{chl} = 122.85(\varrho_{700}/\varrho_{560})^{2.3} \text{ mg} \cdot \text{m}^{-3} \tag{23}$$

with $R^2 = 0.954$, $F = 2046$, $n = 103$.

Fig. 7 presents the relationship between C_{chl} and $\varrho_{700}/\varrho_{560}$ for Lake Balaton. The data obtained allowed to expand the field of application of the radiomodels developed — they turned to be valid for water bodies with $C_{chl} = 5 \text{ mg} \cdot \text{m}^{-3}$ and $C_{sus} = 5 \text{ mg} \cdot \text{l}^{-1}$ on one hand and $C_{chl} = 100 \text{ mg} \cdot \text{m}^{-3}$ and $C_{sus} = 40 \text{ mg} \cdot \text{l}^{-1}$, on the other.

From the data obtained at Lake Balaton in 1986 we developed regression equa-

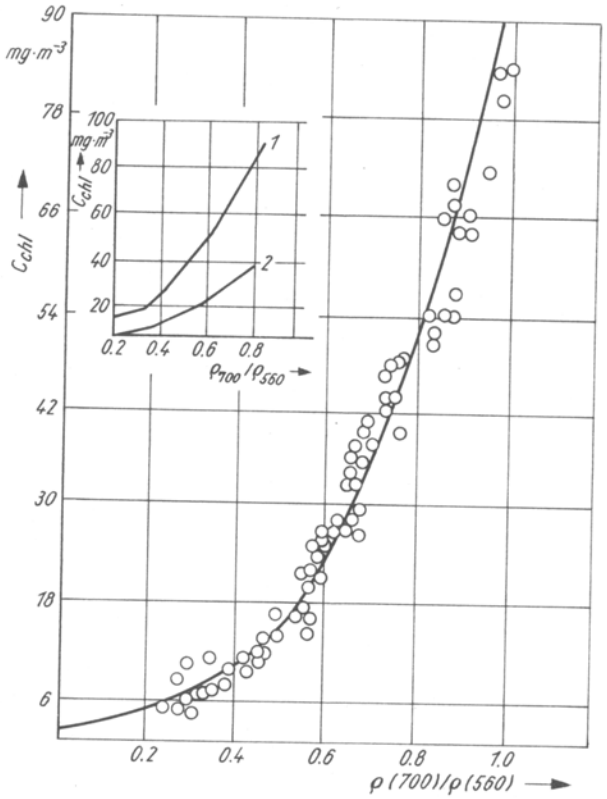

Fig. 7. Relationship between phytoplankton Chlorophyll "a" concentration and $\varrho(700)/\varrho(560)$ ratio for Lake Balaton. At the annex: relationship $C_{chl} = f(\varrho_{700}/\varrho_{560})$: 1 — Lake Balaton, 2 — the rivers Don and Seversky Donetz.

tions of the relationship between C_{chl} and $\varrho_{700}/\varrho_{560}$ parameter. They are the following:

$$C_{chl} = -62 + 184(\varrho_{700}/\varrho_{560}) \text{ mg} \cdot \text{m}^{-3} \tag{24}$$

with $R = 0.94$, $n = 80$,

$$C_{chl} = 140(\varrho_{700}/\varrho_{560})^{2.7} \text{ mg} \cdot \text{m}^{-3} \tag{25}$$

with $R = 0.938$, $n = 30$.

Comparison of the equation (22) to (24) and (23) to (25) indicate that the radiomodel developed is quite stable.

The data of spectrometric measurements of 1986 were used for restoration of C_{chl} values with the model (23) developed from 1985 data. These predicted C^{c}_{chl} values were compared to those obtained in 1985 with contact C^{ex}_{chl} methods (using spectrofluorimeter). The results of the comparison are presented in Fig. 8. Mean square deviations of C^{c}_{chl} values predicted from the true C^{ex}_{chl} value did not exceed 3 mg · m^{-3}.

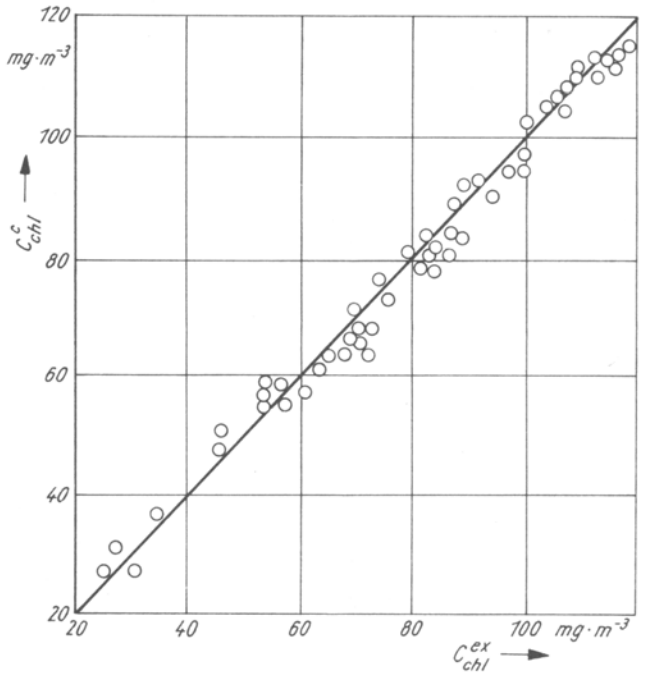

Fig. 8. Comparison of predicted C^{c}_{chl} values calculated from radiomodels with the data obtained with the help of contact methods (C^{ex}_{chl}).

Conclusions

I. In the investigations carried out there was developed the apparatus complex — spectrometers with sequential and simultaneous detection, spectrophotometer, nephelometer, spectrofluorimeter for the investigation of water body radiation parameters together with their hydrochemical and hydrobiological parameters.

2. The methods of quick screening of phytoplankton chlorophyll-a concentration and of the concentration of dissolved organic substances from their fluorescence in the visible spectrum region were developed.

3. Spectral features are isolated from the relationship between SBC and wave length and factors stimulating them are determined.

4. The relationship between the concentrations of phytoplankton chlorophyll-a or suspended mineral substances, respectively, and SBC in the wave band from 440 to 750 nm is defined.

5. The decoding features of optically active ingredients from spectrometric information were determined; they are invariant to survey conditions, an apparatus function of remote sensing instrument and characteristic features of the object controled, related to the phytoplankton species composition and the granulometric composition of mineral suspended substance.

6. Radiomodels of mesotrophic and eutrophic water bodies relating concentrations of mineral and organic suspended substances to water body radioparameters — SBC functional at different waves, were developed from the decoding feature defined.

7. The models developed were tested at different water bodies — rivers (Don, Seversky Donez), lakes (Balaton), Sea of Azov — at concentrations of mineral suspended substances from 5 to 40 $mg \cdot l^{-1}$ and chlorophyll-a from 1.3 to 110 $mg \cdot m^{-3}$.

8. The method of remote sensing of the concentrations of optically active ingredients providing the evaluation of chlorophyll-a concentration (at least 3 $mg \cdot m^{-3}$) and suspended mineral substances (at least 4 $mg \cdot l^{-1}$) was developed on the basis of radiomodels.

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