

STANISŁAW SZPILOWSKI * ANDRZEJ OWCZARCZYK
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**EFFLUENT DISPERSION
IN NATURAL WATER RECEIVERS
(TRACER EXAMINATION)**

INCT-2156/VI



**INSTYTUT CHEMII I TECHNIKI JĄDROWEJ
INSTITUTE OF NUCLEAR CHEMISTRY AND TECHNOLOGY
ИНСТИТУТ ЯДЕРНОЙ ХИМИИ И ТЕХНИКИ**

WARSZAWA 1993

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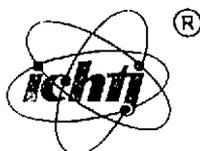
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**INSTITUTE OF NUCLEAR CHEMISTRY AND TECHNOLOGY
DEPARTMENT OF NUCLEAR METHODS OF PROCESS ENGINEERING**

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Dyspersja zanieczyszczeń w naturalnych odbiornikach wodnych (badania znacznikowe)

Metody znacznikowe stwarzają doskonałe możliwości obserwacji i badania procesu rozptyłu i dyspersji ścieków w naturalnych odbiornikach wodnych. W raporcie przedstawiono metody rozwijane i stosowane w Instytucie Chemii i Techniki Jądrowej w celu pomiaru parametrów mieszania w ciekach naturalnych, oznaczania odległości pełnego wymieszania w profilu poprzecznym strumienia, jak również do prognozowania dyspersji ścieków w dużych zbiornikach wodnych. Zaprezentowano także metody określania wstępnej fazy dyspersji ścieków wprowadzanych do dużych naturalnych zbiorników wodnych przy pomocy zrzutów podwodnych oraz metodę określania szybkości procesów naturalnego samoczyszczenia cieku. Zaprezentowane metody mogą być z powodzeniem zastosowane w analizie zatrucia wód danego regionu, przy wyborze optymalnej lokalizacji produktów zrzutu ścieków do odbiornika naturalnego, jak również przewidywania intensywności rozptyłu w różnych warunkach hydrometeorologicznych.

Effluent dispersion in natural water receivers (tracer examination)

Tracer methods constitute very convenient means for observation and examination of effluent dispersion and dilution processes in natural water receivers. In the report there are presented methods developed and used by the Institute of Nuclear Chemistry and Technology (INCT) to measure mixing parameters in natural streams to determine distances of complete transverse mixing as well as to assess and predict dispersion of sewage in large water reservoirs. There are also presented the methods of predicting initial stage of dispersion of sewage discharged into large water reservoirs through underwater outfalls and the method for determining the decomposition rates of effluent entering a natural water receiver. The methods presented can be used in analysis of pollution in a given water region, in selection of optimal sewage outfall locations as well as in prediction of effluent dilution intensity at different hydro- and meteorological conditions.

Дисперсия загрязнений в натуральных водных приемниках (индикаторные исследования)

Индикаторные методы создают большие возможности наблюдения и исследования процессов дисперсий сточных вод в натуральных приемниках воды. В отчете представлены разрабатываемые и применяемые в Институте Химии и Ядерной Техники методы измерения параметров смешивания в натуральных водах, определения

длины полного смешивания в поперечных сечениях струй а также для прогнозирования дисперсий стоков в больших водных бассейнах. Представлены методы определения начальной фазы дисперсии стоков вводимых в большой естественный бассейн при помощи подповерхностного сброса а также методы определения скорости процесса естественной самоочистки воды. Представляемые методы могут применяться для анализа загрязнений вод данного района, оптимизаций локализаций мест сброса стоков в естественных приемниках воды а также для предвидения интенсивности рассеяния стоков при разных гидрометеорологических условиях.

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1. INTRODUCTION

Surface waters are a primary receiver for wastes discharged in liquid form. Continuous expansion of industrial activities and urban agglomerations results in still increasing amount of pollutants discharged into rivers, lakes and coastal sea areas. This results in harmful effects on environment equilibrium in natural water reservoirs affected with discharged pollutants leading in extreme cases, to complete disappearance of biological life in water regions highly loaded with pollutants. On the other hand, the surface waters constitute one of most important water sources for municipal and industrial use. High degree of their pollution, beside of technical difficulties associated with treatment of water in order to make it suitable for both household and process purposes, creates numerous hazards of secondary nature through various kinds of potable water, fish and industrial water contamination.

Various activities are being undertaken to reduce pollution of surface waters. One of possible measures of this nature is adequate design and appropriate choice of location of sewage outfall so as to enable rapid dilution of pollutants in a water receiver to cause in consequence rapid reduction in concentration of pollutants. Low concentration of pollutants acts in favor of efficient biological activity of natural receiver resulting in gradual self-purification of water.

Successful protection of surface water against excessive contamination requires sufficient knowledge of phenomena occurring in transport of pollutants in natural water receivers. It results in increasingly high interest in studies of interrelations between natural waters and wastes discharged there. The studies are particularly designed for dispersion of pollutants and intensity of their mixing with water of natural receiver, self-purification mechanisms, kinetics of the self-purification process as well as optimized design and appropriate location of sewage outfalls.

One of the research tools being used in solving problems of the above described nature are tracer methods. This report is aimed to present main directions of research works being carried out by the INCT in the field of tracer method application in investigations of dispersion and dilution and decomposition of pollutants in surface waters.

2. TRACERS

Practical use of tracer method in investigation of processes occurring in liquid flow consists in introduction into a flowing medium a substance following the behaviour of the medium concerned but having predetermined property enabling to distinguish it from the medium labelled therewith. This specific feature of a tracer enables to detect it by recording its concentration as a function of time. The time concentration characteristics obtained in this way are a basis for analyzing the processes occurring in the system under test. The physicochemical properties of various kind can be used for detection of tracers, for example, an electrolyte solution causing changes in

electrochemical properties of investigated medium. In order to determine a tracer content the conductivity, photometric, fluorescence and radiometric techniques are used.

In investigation of dispersion and dilution of pollutants in surface waters the radioactive and fluorescent tracers are widely used. These two kinds of tracers are highly stable in aqueous media and are featured by high sensitivity of their detection.

A tracer being used in investigation of pollutant transport and dilution processes has to satisfy a number of requirements. The most important of them is that being initially labelled therewith. This means that occurrence to a substantial extent of such processes as sorption of a tracer on suspensions and bottom deposits, extraction thereof by foreign phases and its precipitation with sediments have to be precluded.

A study on suitability of tracers has resulted in selection of ^{82}Br in the form of aqueous solution of KBr as a radioactive tracer [1] and of rhodamine-WT (rhodamine-B) and uranine as fluorescent dyes. These tracers have been for years successfully used to study the process of transport and dispersion of pollutants in natural water receivers [2-11].

There is a trend to use rather fluorescent dyes as the cost of them is much lower than that of radioactive tracers. On the other hand, the application of fluorescent tracers is limited to water regions of relatively low pollution. High concentration of pollutants, especially of oil products, causes the tracer loses relatively quickly its fluorescent properties. Therefore, the investigation of a certain water region is usually preceded by triple-tracer experiment consisting in simultaneous injection of radioactive and fluorescent tracers in order to determine the rate of disappearance of the fluorescence. In such a test the radioactive tracer is used as a reference substance. Radioactive disintegration occurs at predetermined rate being independent of changes in chemical composition of an ambient medium and therefore its detection is independent of such factors as salinity, coloration and pH of a medium under investigation as well as of presence of foreign phases.

Major disadvantages of radioactive tracers are: their relatively high price and necessity of taking special precaution during preparation of a tracer for use and while introducing it into a given water region. The only factor restricting suitability of ^{82}Br in the form of KBr labelling aqueous phases is the possible presence of substances causing precipitation or extraction of Br^- ions.

3. MEASUREMENT OF TRACER CONCENTRATION IN NATURAL WATER RECEIVERS

Tracer investigation of pollutant transport in surface waters consists in injection of a tracer at a predetermined point of the water region under test and recording distribution of its concentration as a function of time and position within that region.

Continuous injection of a tracer is the way of introducing it which gives the direct approximation of actual discharge of pollutants. In such case the recorded distribu-

tions of tracer concentration are proportional to concentration of dissolved pollutants along corresponding axes.

Another possible way of introducing a tracer is its instantaneous injection. In this case the corresponding dilution values are obtained after making the activity (or mass) balance calculations. Both methods are equivalent as for quantity and quality of information furnished concerns. The latter is most frequently used in practice because it requires smaller amount of a tracer as compared with continuous introduction and tracer injecting equipment being used is less complicated.

3.1. Measuring equipment

Pollutant dispersion survey requires the knowledge of the tracer concentration at multiple points within a water region under investigation. It is impossible, for both engineering and economical reasons, to install such a large number of individual stationary measuring points. Therefore a single mobile measuring station is being used.

The measurement of radioactive tracer concentration distribution is being made by means of a scintillation probe (NaI/Tl) connected to a counting and data recording

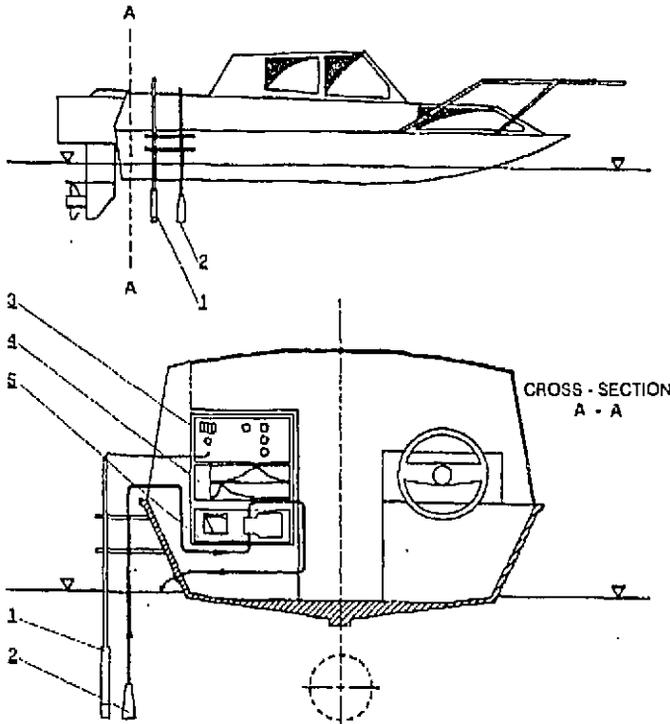


Fig.1. Detection of radioactive and fluorescent tracers. 1 - scintillation probe, 2 - submersible pump, 3 - field radiometric set, 4 - recorder, 5 - continuous flow fluorometer.

system. The INCT employs for that purpose the RZP-10 field radiometric sets. Each of such sets consists of a high-voltage power supplier for the SSU-70 scintillation probe, single-channel amplitude analyzer being used to select optimum counting window within the tracer's γ - radiation energy spectrum, and a specialized computer. The set is provided with adjustable counting time interval unit within the range from 0.1 to 100 s. There is also a digital display on the front panel of the set to display measurement results being then recorded, after conversion into voltage signal, on a recorder tape (as a function of time).

For detection of fluorescent tracers [12] the Turner Design field fluorometer Model 10-005 provided with a set of filters for detection of fluorescent tracers and continuous flow cuvette system is used. This fluorometer version is adapted for continuous measurement of tracer concentration in water pumped through the continuous-flow cuvette. Results can be read on a fluorometer display and, recorded as a function of time.

Both measuring sets are of portable field type and require DC power supply of 12 V. This kind of measuring equipment enables to make measurements without collection and storage of samples. The measuring equipment described above is installed aboard of a speed-boat (Fig.1).

3.2. Navigation

Measurements of distributions of tracer concentration are made from the measuring vessel (Fig.1) moving at constant speed and along a predetermined path over a water region under investigation. Data obtained require to be related to corresponding positions of the measuring vessel and to time lapsed from injection of tracer. The second problem is solved by recording the measurement data as a function of time. Continuous tracing of the vessel's position is impossible and therefore only selected positions are being determined.

Various methods are applied to determine the vessel's position. Two methods are used for natural streams:

- First one consists in establishing measurement profiles and marking them by visual aids placed on the water (anchored floats). Positions of the aids are determined by the intersection method using theodolites. The measuring vessel sails along the profile during recording the tracer time-concentration curves. The points corresponding to respective positions of floats are marked on the recorder strip.
- Another method consists in application of microwave range-finder to fix the vessel's positions on a measuring profile.

Three methods are used for coastal water:

- First of them consists in taking two simultaneous bearings from two points located on the waterside of water region under investigation. The bearings are taken in respect to base line connecting the two points. In that way two position lines are obtained and their intersection point is the vessel's position at a given time. These bearings are taken by means of theodolites simultaneously to a command given

from the boat by radio. This method is illustrated schematically in Fig.2A. Usually the position is given in cartesian coordinate system (x,y) . To obtain such position coordinates it is necessary to solve a system of equations of two straight lines with their respective slopes $\text{tg } \alpha_1$ and $\text{tg } \alpha_2$, where α_1 and α_2 are respective values of the two simultaneous bearings.

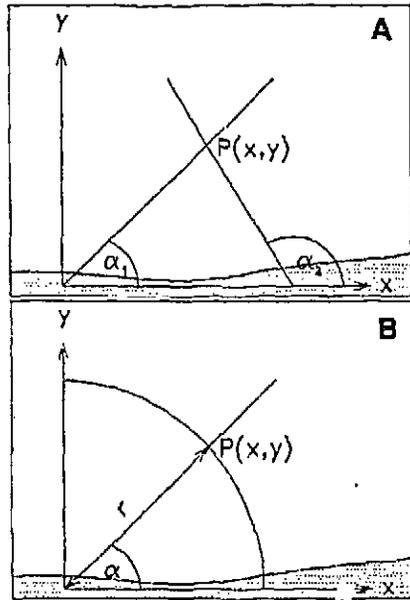


Fig.2. Schematic illustration of determining the position of measuring vessel. A - two simultaneous bearings, B - simultaneous bearing and distance measurement.

- Second method being used to determine positions of the measuring vessel is the method employing a bearing taken from a single point on the waterside and measurement of distance between that point and the vessel. In implementation of this method a microwave range-finder coupled with a theodolite is used. Initial data necessary to calculate the vessel's position are then: the bearing (α) and the distance (r). These data, similarly as in the two bearings method, are used to calculate cartesian coordinates (x,y) of the vessel's position. In this case, the position is given by the intersection point between position line defined by its slope $\text{tg } \alpha$ and circle of radius r . This method is illustrated schematically in Fig.2B.
- Another method consists in using nationwide positioning systems (if available on area under consideration) or portable radionavigation systems.

3.3. Methodology of experimental work

In investigation of pollutant transport and dispersion processes the instantaneous tracer injection method is most frequently used [4, 5, 7-10]. A tracer is injected directly into waste water discharged into the water receiver or, if the investigation is intended to optimize sewage outfall location, at points initially considered as suitable for sewage discharge. The measurement technique of tracer concentration distribution to be used depends on hydraulic conditions prevailing in a water region under investigation. Two basic measuring methods are distinguished. One of them is suitable for the use in natural streams and another suited to use in large water reservoirs (lakes, coastal water).

3.3.1. Rivers

The tracer method is being used in investigation of pollutant spreading and in measurements of dispersion coefficients in rivers. It consists in instantaneous injection of a tracer at selected point of river cross-section and recording tracer

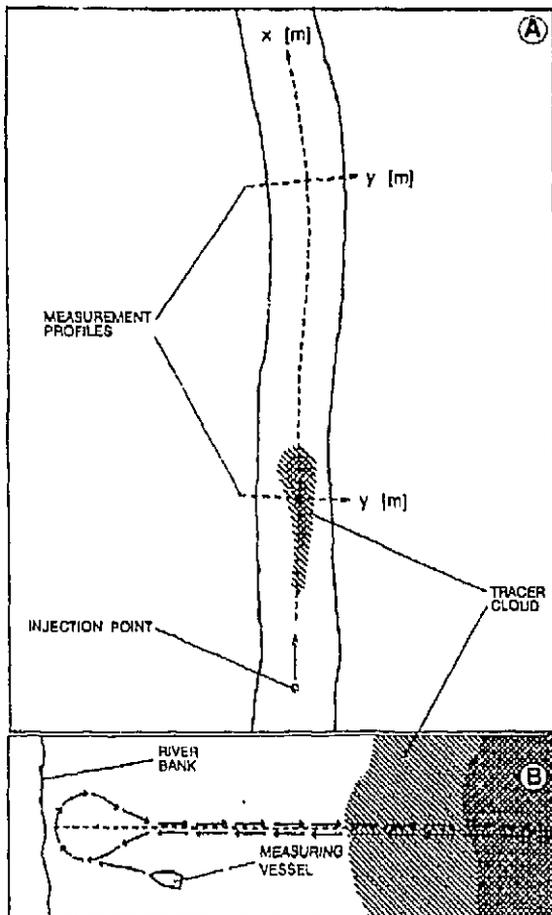


Fig.3. The principle of measurement of the transverse distribution of tracer concentration in natural stream. A - the measurement profiles, B - the course of measuring vessel.

concentration distribution over river width as a function of time at predetermined distances from the injection point. For this purpose a number of measurement profiles is being established (Fig.3A). Each of them is marked with two or more anchored floats (Fig.3A). Their positions are determined by intersection method. Distribution of tracer concentrations is being measured by making a set of timed runs of measuring vessel along a given profile during the time when tracer cloud crosses the line connecting marking floats. During each run along the profile the tracer concentration is being recorded as a function of time (Fig.3B). The positions of measuring vessel are fixed by one of methods described under 3.3. above. In this way each point of recorded concentration distribution curve is defined by two coordinates: one of them indicates the position on river width axis and another being a time coordinate.

The final result of the experiment is an array containing the tracer concentration values with corresponding positions on the $0,y$ axis and time coordinates.

Since sampling of the curves being recorded proceeds at constant Δy step, the obtained array has the following form:

$$\begin{array}{ccccccc}
 \alpha(y_{1,1}, t_{1,2}) & \alpha(y_{1,2}, t_{1,2}) & \dots & \alpha(y_{1,j}, t_{1,j}) & \dots & \alpha(y_{1,k}, t_{1,k}) & \\
 \alpha(y_{2,1}, t_{2,1}) & \alpha(y_{2,2}, t_{2,2}) & \dots & \alpha(y_{2,j}, t_{2,j}) & \dots & \alpha(y_{2,k}, t_{2,k}) & \\
 \dots & \dots & \dots & \dots & \dots & \dots & \\
 \alpha(y_{i,1}, t_{i,1}) & \alpha(y_{i,2}, t_{i,2}) & \dots & \alpha(y_{i,j}, t_{i,j}) & \dots & \alpha(y_{i,k}, t_{i,k}) & (1) \\
 \dots & \dots & \dots & \dots & \dots & \dots & \\
 \alpha(y_{N,1}, t_{N,1}) & \alpha(y_{N,2}, t_{N,2}) & \dots & \alpha(y_{N,j}, t_{N,j}) & \dots & \alpha(y_{N,k}, t_{N,k}) &
 \end{array}$$

where:

$$i = 1, 2, 3, \dots, N \quad (2)$$

$$j = 1, 2, 3, \dots, K \quad (3)$$

In the array (1) rows represent selected points of the tracer concentration distribution along the O, y axis sampled at given Δy_{step} (single row - single run of the measuring vessel), while columns express selected points of the tracer concentration distribution in time (single column - single time-distribution curve recorded at j -th point of O, y axis).

The procedure described above is repeated for each of measurement profiles being marked out. So acquired data, after making appropriate corrections taking into account present pulse counting interval (or fluorometer delay) and decay rate of a tracer, are sufficient to determine distribution of dilution of discharged pollutants along a given measurement profile as well as coefficients of longitudinal and transverse dispersion.

3.3.2. Water reservoirs

Tracer investigation of pollutant transport in big water reservoirs serves the purpose of acquiring data of the same nature as those described under 3.3.1. above. It is necessary to use another measuring technique in such cases, because of different hydrologic characteristics of water regions examined. Directions and velocity of pollutant transport are dependent to substantial extent on currently prevailing hydraulic conditions. In particular, wind direction and velocity are the factors essentially influencing the nature of pollutant dispersion. Under such

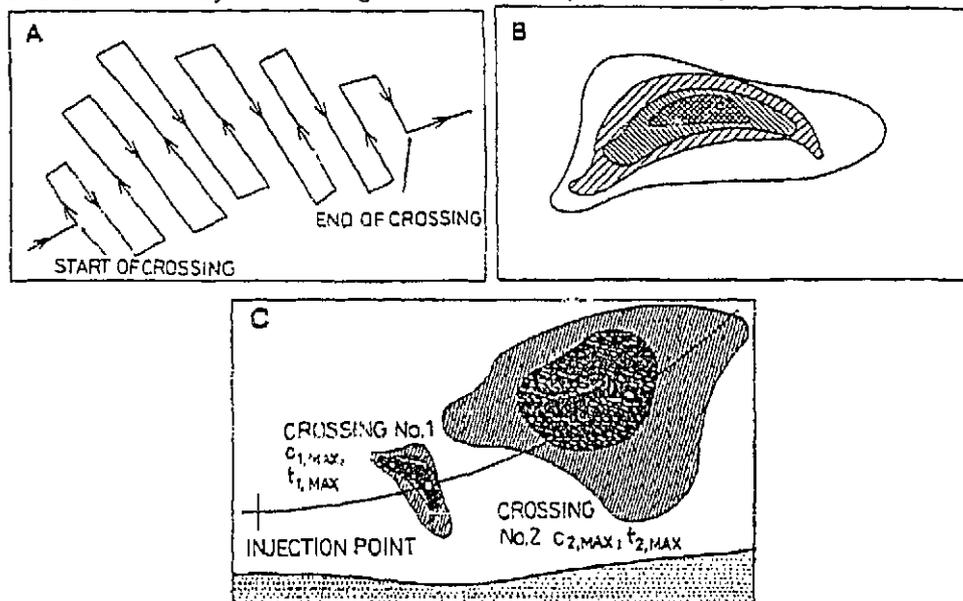


Fig.4. The principle of tracer concentration measurement in big water reservoir. A - plot of the course of measuring vessel, B - isoconcentration lines, C - example of isoconcentration lines obtained after tracer injection.

circumstances, the measurements made along previously marked out measurement profiles are completely useless. It is much more convenient to use the method leading to determination of isoconcentration lines. Therefrom it is possible to obtain concentration distribution curves along any optionally chosen axis. While implementing this method tracer concentration measurements are being made from a measuring boat sailing over a region of tracer plume. An example of tracer path followed by the measuring vessel during such measurements is shown in Fig.4A. Successive vessel's positions are being determined using any of the methods described previously under 3.2.

An example of isoconcentration lines obtained as result of such tracer experiment is shown in Fig.4B. Beside of corrections taking into account a time characteristics of measuring equipment used and rate of tracer decay also those resulting from interrelations between vessel's velocity on one hand and water current vector magnitude on the other are being made. A complete measuring cycle during such investigation consists of tracer injection at selected point of the water region under test and determination of a series of isoconcentration successive sets of different time intervals from tracer injection (Fig.4C). Because of the fact that the tracer transport and dispersion process occurs at much slower rate than in natural streams it has been assumed that dispersion rate of tracer plume does not change during a single measuring sequence intended to determine a given set of isoconcentration lines.

4. TRANSPORT AND DISPERSION OF POLLUTANTS IN RIVERS

4.1. Dispersion equation

Among various phenomena associated with mass transport in liquid streams there is one coming distinctly to the fore, namely gradual increase in homogeneity of concentration of all substances taking part in that process. Ultimate result thereof is complete homogeneity of concentration within the whole stream. Basic indicative attributes of dispersion mechanism of the mass transport process are the gradients of velocity field and pulsations of the latter. A logical starting-point for considering any process of this nature is the mass balance equation for substances being convected by and dispersed within a flowing medium. This equation takes the following form for flows of incompressible fluids [13]:

$$\frac{\partial \phi}{\partial t} + u_i \frac{\partial \phi}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\epsilon_m \frac{\partial \phi}{\partial x_i} \right) \quad (4)$$

where:

ϕ - concentration of substance being transported;

t - time;

x_i - i -th direction coordinate;

u_i - local value of flow velocity along O, x_i axis;

ϵ_m - molecular diffusion coefficient.

The equation (4) describes the balance of mass flowing through a given surface area (or intensity of mass exchange within a given volume) and does not include any assumptions associated with mixing mechanism. Therefore it constitutes a basis for any phenomenological description of all mass transport processes in liquid streams.

For a turbulent mixing process the quantities u_i and ϕ are the sums of time-averaged and fluctuating time-dependent terms [14,15]:

$$u_i = U_i + u_i' \quad (5)$$

$$\phi = \Phi + \phi' \quad (6)$$

where:

$$U_i = \frac{1}{T} \int_0^T u_i'(t) dt \quad \text{and} \quad \Phi = \frac{1}{T} \int_0^T \phi'(t) dt \quad (7)$$

After replacing corresponding terms of the equation (4) with (5) and (6) respectively an additional term is obtained which describes the fluctuations. This term is regarded as a quantity proportional to the local gradient of time-averaged concentration value and its factor of proportionality is a constant describing turbulent mixing intensity:

$$-\overline{u_i' \phi'} = \frac{1}{T} \int_0^T u_i'(t) \phi'(t) dt = \epsilon_{ij} \frac{\partial \Phi}{\partial x_j} \quad (8)$$

The quantity of ϵ_{ij} is a constant or a second order tensor, where $j = 1, 2, 3$. Taking the above into account the equation (4) will take the following form:

$$\frac{\partial \Phi}{\partial t} + u_i \frac{\partial \Phi}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\epsilon_m + \epsilon_{ij} \frac{\partial \Phi}{\partial x_j} \right) \quad (9)$$

From the equation (9) it results that local changes in Φ and those associated with convection are caused by molecular and turbulent diffusion. Interaction between both diffusion processes can appear to be extremely complex one and dependent on intensities of both processes [16, 17].

Possible simplifying assumptions being made depend also on the scale of the process under investigation. It is assumed while investigating liquid flow and mixing processes in open channels and reservoirs that the smallest distinguishable "labelled particle" is much larger than a molecule and much smaller than the smallest volume taking part in mass exchange caused by turbulent flow. In that way the molecular mixing takes place only within "labelled particles" and in the case of processes when their scale exceeds many times the size of such particle the molecular mixing process can be neglected. While designating the concentration of "labelled particles" with c it is then possible to introduce this quantity directly into the equation (9). As result the following equation is obtained:

$$\frac{\partial c}{\partial t} + u_i \frac{\partial c}{\partial x_i} = \frac{\partial}{\partial x_i} \left(D_{ij} \frac{\partial c}{\partial x_j} \right) \quad (10)$$

The quantity D_{ij} is a mass transfer coefficient which characterizes diffusion of "labelled" particles during a turbulent flow and the quantity c is averaged according to the equation (7). If the orientation of $0, x_i$ axes is consistent with that of the three-dimensional cartesian coordinate system then [18]:

$$D_{ij} = 0 \text{ for } i \neq j \text{ and } D_{ij} = D_{ii} \text{ for } i=j \quad (11)$$

Further by designating the axes with $0, x, 0, y, 0, z$ respectively and their corresponding velocities with u, v, w , the following equation is obtained:

$$\frac{\partial c}{\partial t} + u \frac{\partial c}{\partial x} + v \frac{\partial c}{\partial y} + w \frac{\partial c}{\partial z} = D_x \frac{\partial^2 c}{\partial x^2} + D_y \frac{\partial^2 c}{\partial y^2} + D_z \frac{\partial^2 c}{\partial z^2} \quad (12)$$

The quantities: D_x, D_y, D_z are the coefficients of longitudinal, transverse and vertical dispersion respectively. Their values constitute a measure of intensities of dispersion in directions of corresponding axes of the coordinate system. The equation (12) is a basic for attempts, continued for many years, to derive mathematical models describing relationship between turbulence intensity and averaged flow characteristics. Presently an abundant bibliography concerning studies on processes associated with a flow of liquids is available. It must be stressed, however, that these papers are not of general nature. Simplifications adopted therein in respect to mechanisms of investigated processes impose substantial limitations on the scope of their application, confining the latter to definite cases only and data obtained are more or less inaccurate approximations of actual values. In such situation the measurement of real distributions of tracer seems to be most reliable source of information about dispersion process.

Solutions of the equation (12) for instantaneous injection of a tracer when water-sides do not affect distribution of tracer concentration are known [19] and have the following forms.

For one dimensional dispersion (in direction of axis $0, x$):

$$c = \frac{A}{S (4\pi D_x t)^{1/2}} \exp \left[-\frac{(x - ut)^2}{4D_x t} \right] \quad (13)$$

For two dimensional dispersion (in directions of $0, x$ and $0, y$ axes):

$$c = \frac{A}{4\pi H t (D_x D_y)^{1/2}} \exp \left\{ -\left[\frac{(x - ut)^2}{4D_x t} + \frac{(y - vt)^2}{4D_y t} \right] \right\} \quad (14)$$

For three dimensional dispersion (in directions of $0, x; 0, y$ and $0, z$ axes):

$$c = \frac{A}{(2\pi t)^{3/2} (8D_x D_y D_z)^{1/2}} \exp \left\{ -\left[\frac{(x - ut)^2}{4D_x t} + \frac{(y - vt)^2}{4D_y t} + \frac{(z - wt)^2}{4D_z t} \right] \right\} \quad (15)$$

where:

A - total tracer amount (mass or activity);

S - cross-section area of the stream;

H - depth of the stream.

Because of relatively low value of depth as compared to width of the natural stream it is obvious that homogenization of tracer concentration in vertical direction is normally achieved during the time many times shorter than in transverse direction.

While carrying out the tracer investigation of dispersion process the $0, x$ axis is assumed to be the line with direction in which displacement of maximum tracer concentration takes place. Therefore the transverse flow velocity component (v) is not measured and has no influence on dispersion of recorded tracer concentration both in time and over width of the stream under test. This causes that the dispersion process is described by the following equation:

$$c = \frac{A}{4\pi Ht (D_x D_y)^{1/2}} \exp \left\{ - \left[\frac{(x - ut)^2}{4D_x t} + \frac{y^2}{4D_y t} \right] \right\} \quad (16)$$

This equation relates to the stage of dispersion process before a cloud of the substance being transported reaches sides of the stream involved. Further analysis of that process requires to take into account the effects of river sides and position of tracer injection point on the axis $0, y$. The equation (12) written for the above described condition and for instantaneous injection of a tracer as well as for two dimensional dispersion has the following form:

$$\frac{\partial c}{\partial t} + u \frac{\partial c}{\partial x} = D_x \frac{\partial^2 c}{\partial x^2} + D_y \frac{\partial^2 c}{\partial y^2} + A \delta(x - x^*) \delta(y - y^*) \delta(t - t^*) \quad (17)$$

$$x \in (-\infty, +\infty) \quad (18)$$

$$y \in [0, B] \quad (19)$$

with initial condition:

$$c = 0 \quad \text{for } t = 0 \quad (20)$$

and the boundary conditions:

$$c = 0 \quad \text{for } x \rightarrow \pm\infty \quad (21)$$

$$\frac{\partial c}{\partial y} = 0 \quad y = 0 \quad (22)$$

$$\frac{\partial c}{\partial y} = 0 \quad y = B \quad (23)$$

where:

B - width of the stream;

x^*, y^*, z^*, t^* - position and time coordinates of the injection;

δ - Dirac function.

Solution of the equation (17) consists in making Fourier transformation of variables x, y in order to obtain an ordinary differential equation in time domain, solving this equation and making inverse Fourier transformation in order to obtain solution in the form of $c = f(x, y, t)$. This solution has the following form:

$$c(x,y,t) = \frac{2A \exp[-(x-x^* - ut)^2]}{4D_x t} \frac{1}{B(4\pi D_y t)^{1/2}} \left\{ 1 + 2 \sum_{n=1}^{\infty} \exp\left(-n^2 \pi^2 \frac{D_y t}{B^2}\right) \cos \frac{n\pi y}{B} \cos \frac{n\pi y^*}{B} \right\} \quad (24)$$

The equation (24) describes distribution along axes O,x ; O,y of concentrations of tracer instantaneously injected at a point of (x^*,y^*) coordinates, after time t from tracer injection.

4.2. Measurement of dispersion coefficients values

The equation (16) constitutes a relationship describing unimodal two dimensional statistical distribution. Equations of this kind have the following properties:

$$2\sigma_x^2 = 4D_x t \quad (25)$$

$$2\sigma_y^2 = 4D_y t \quad (26)$$

Therefore the dispersion coefficients can be calculated from a variance of tracer concentration distributions along axes O,x and O,y :

$$D_x = \frac{\sigma_x^2}{2t} \quad (27)$$

$$D_y = \frac{\sigma_y^2}{2t} \quad (28)$$

Measurement of the dispersion coefficients values consist in instantaneous injection of a tracer at the center of river cross-section and recording tracer concentration distribution in measurement profiles marked out at different distances from a tracer injection point. In survey work of that kind the measurement technique described under 3.3.1. is being used. As result of such measurements the curves of tracer concentration distribution in time and along river width are obtained. In this case the equations (27) and (28) can not be used directly for calculation of D_x and D_y values. The values of σ_x^2 and σ_y^2 in the formulae (27) and (28) are related to distributions $c = f(x)$ and $c = f(y)$ determined instantaneously at the time corresponding to passage of maximum concentration in a tracer plume across the measurement profile concerned. The experimental distributions $c = f(t)$ and $c = f(y)$ are determined within a finite time interval. In this situation the equation (16) must be appropriately rearranged in order to satisfy conditions resulting from measuring technique being applied.

A relationship describing distribution of tracer concentration along axis O,x - being in line with direction of maximum concentration spot displacement within a tracer plume - is obtained by inserting into the equation (16) the value $y = 0$. So rearranged equation resolves itself into dimensionless form by introducing the following substitutions:

$$c^* = \frac{cHL^2}{A} \quad (29)$$

$$\xi = \frac{ut}{L} \quad (30)$$

$$\phi = \frac{D_x}{uL} \quad (31)$$

$$\psi = \frac{D_y}{uL} \quad (32)$$

As results of the above the equation (16) takes the following from:

$$c^* = f(\xi) = \frac{1}{4\pi\xi(\phi\psi)^{1/2}} \exp\left[-\frac{(1-\xi)^2}{4\xi\psi}\right] \quad (33)$$

The equation (33) represents, in dimensionless form, the variability of tracer concentration in the time domain at a distance $x = L$ from tracer injection point. The variance of $c^* = f(\xi)$ function is given by the following equation:

$$\sigma_f^2 = \frac{\int_0^\infty \xi^2 c^*(\xi) d\xi}{\int_0^\infty c^*(\xi) d\xi} - \left[\frac{\int_0^\infty \xi c^*(\xi) d\xi}{\int_0^\infty c^*(\xi) d\xi} \right]^2 \quad (34)$$

After solving the integrals in the equation (34) the following equation is obtained:

$$\sigma_f^2 = 4\phi \frac{N_1\left(\frac{1}{2\phi}\right) + N_0\left(\frac{1}{2\phi}\right)}{N_0\left(\frac{1}{2\phi}\right)} - \left[\frac{N_1\left(\frac{1}{2\phi}\right)}{N_0\left(\frac{1}{2\phi}\right)} \right]^2 \quad (35)$$

where:

$$\sigma_f^2 = \frac{u^2 \sigma_f^2}{L^2} \quad (36)$$

N_0, N_1 - Neumann functions:

$$N_n(x) = \left(\frac{\pi}{2x}\right)^{1/2} \exp(-x) \left\{ 1 + \sum_{m=1}^{\infty} \frac{\prod_{k=1}^m 4n + (2k-1)^2}{m!(8k)^m} \right\} \quad (37)$$

The equation (35) enables to determine the coefficient of longitudinal dispersion having known the variance σ_f^2 of tracer concentration distribution as a function of time determined for a given distance L from tracer injection point. In order to determine the coefficient of transverse dispersion the equation (16) is being reduced to the form of dimensionless relationship in the time domain:

$$c^* = g(\xi) = \frac{1}{4\pi\xi(\phi\psi)^{1/2}} \exp \left\{ -\frac{(\alpha\phi + \psi) + (1 - \xi)^2}{4\xi\phi\psi} \right\} \quad (38)$$

where:

$$a = \frac{(v')^2}{u^2} \quad (39)$$

v' - velocity of measuring boat.

The variance of $c^* = g(\xi)$ function is being determined in accordance with the relationship (34) and expressed by the following equation:

$$\sigma_g^2 = \frac{4\phi\psi}{\alpha\phi + \psi} \frac{N_1 \left(\frac{\alpha\phi + \psi}{2\phi\psi} \right) + N_0 \left(\frac{\alpha\phi + \psi}{2\phi\psi} \right)}{N_1 \left(\frac{\alpha\phi + \psi}{2\phi\psi} \right)} - \left[\frac{N_1 \left(\frac{\alpha\phi + \psi}{2\phi\psi} \right)}{N_0 \left(\frac{\alpha\phi + \psi}{2\phi\psi} \right)} \right]^2 \quad (40)$$

where:

$$\sigma_g^2 = \frac{\sigma_y^2}{L^2} \quad (41)$$

Table 1. Summary of results of dispersion coefficient measurements

Measurement location (tracer)		Distance from injection point	Mean transport time	Mean flow velocity	Longitudinal dispersion coefficient	Transverse dispersion coefficient
		L	T	u	D_x	D_y
		m	s	m/s	m ² /s	m ² /s
Vistula river Warsaw area, Poland (⁸² Br)	1980.04.14	560	479	1.17	2.12	0.298
		980	860	1.14	1.86	0.272
		1360	1204	1.13	2.07	0.308
		2240	2000	1.12	2.05	0.224
	1983.10.08	420	355	1.18	1.78	0.261
		2425	2177	1.13	1.99	0.133
		3175	2857	1.11	2.75	0.207
	1986.05.11	2415	2506	0.96	1.72	0.220
		3590	3705	0.97	1.94	0.206
		5305	5420	0.98	2.15	0.254
		7205	7600	0.95	1.65	0.215
	Vistula river Polaniec area, Poland (rhodamine - B)	1984.08.21	1614	2101	0.768	0.807
2269			3469	0.654	1.93	0.123
3018			4614	0.654	3.23	0.117
4252			6665	0.638	3.66	0.203

According to the equation (40) the variance σ_y^2 of tracer concentration distribution curve, determined along width of a stream by means of mobile measuring stand moving at speed of v' across a river at a given distance L from tracer injection point, is a function of coefficients of longitudinal and transverse dispersion, and of the ratio of squares of measuring stand speed and mean flow velocity of water in a river.

In Table 1, the values of dispersion coefficients determined by means of the equations (35) and (41) on the basis of results of tracer investigations [8,10] are given. The determined values constitute a measure of the extent of dilution of pollutants discharged into a river and have been used for prediction of sewage spreading therein.

4.3. Mixing degree

Pollutants continuously discharged into a natural stream undergo gradual dilution over its cross-section. This process terminates when completely uniform concentration of pollutants over width of a stream is reached. From the view-point of water pollution control it is desirable that such a process terminate within possible shortest distance from the outfall. It is obvious that the rate of attaining the state of uniform dilution depends on transverse mixing conditions prevailing within a given stream [20]. The possibility of influencing this by intentional human activity is very little. In such situation it is essential to know how the mixing rate is influenced by changing the position of discharge point along the river width. To this the term of transverse mixing degree M has been introduced [21]:

$$M = 1 - \left[\frac{1}{N} \sum_{i=1}^N \left(1 - \frac{c_i}{\bar{c}} \right)^2 \right]^{1/2} \tag{42}$$

where:

c_i - concentration of pollutant at i -th point of $O'y$ axis;

$$i = 1, 2, 3, \dots, N \tag{43}$$

\bar{c} - mean concentration of pollutant in stream cross-section.

The value of M varies between 0 and 1. $M = 1$ means complete homogeneity over the whole cross-section of the stream. In order to follow changes in value of M in dependence on position of discharge point on the $O'y$ axis (y^*) a series of calculations

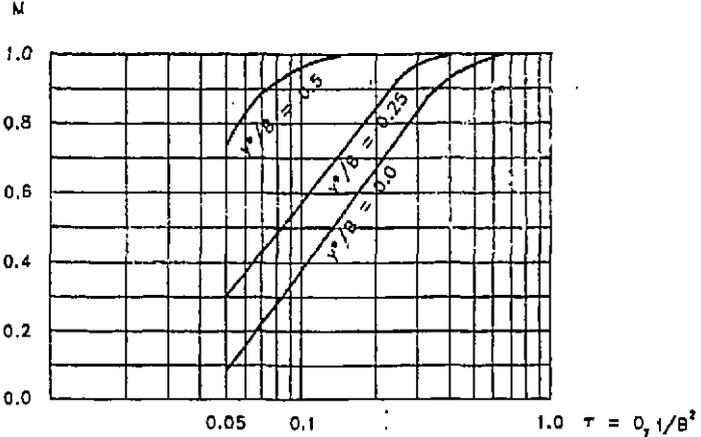


Fig.5. The curves $M = f(D, t/B^2)$ calculated for different positions of discharge point (y') on river width axis. $y'/B = 0.0$ - riverside, $y'/B = 0.5$ - stream centre.

of mixing degree for different values of dimensionless transport time ($\tau = D_y t / B^2$) were made. The measured values of transverse dispersion coefficient were used in calculations. The results are shown in Fig.5. The positions of discharge point are indicated in a dimensionless scale y^*/B .

The curves $M = f(\tau)$ indicate that most favorable mixing conditions exist when discharge point is situated in the center of the stream. Change of this position causes sudden decrease in mixing intensity over cross-section.

The procedure of evaluation of mixing degree values has been verified by making a series of tracer measurements in Vistula river near Warsaw (Poland) [8]. Rhodamine-B and uranine were used as the tracers. The investigation was carried out over a long (about 30 km) reach of river. The tracers were injected in the middle of river width ($y^*/B = 0.5$), at some distances from that point ($y^*/B = 0.4$) and at the riverside ($y^*/B = 0$). For tracer concentration distributions recorded at long distances from injection point values of mixing degree were calculated. Results, in the form of curves $M = f(\tau)$, are shown in Fig.6. The curves representing relationship between mixing degree and dimensionless transport time determined on the basis of measured values of dispersion coefficients show satisfactory agreement with real values.

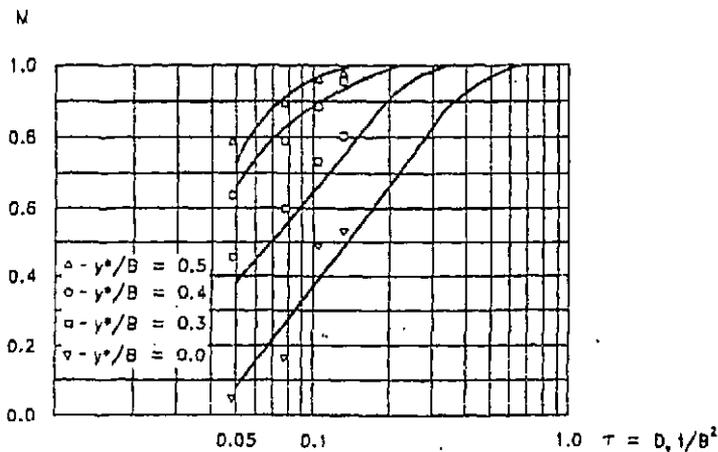


Fig.6. The curves $M = f(D_y t / B^2)$ calculated for different positions of discharge point (y^*) on river width axis and respective measured values (Vistula river Warsaw area, Poland).

This means that the method consisting in use of dispersion coefficient values determined by tracer method is suitable for prediction of mixing degree of pollutants at different distances from discharge point as well as for prediction of distance required for complete transverse mixing. Knowing the initial concentration of pollutants it is possible to estimate the river pollution with both intended or existing sewage disposal.

The tracer technique of evaluation of mixing degree was applied to select the optimal location of petrochemical effluent outfall into the river. The field investigations were carried out on Vistula river in Plock area (about 100 km north of Warsaw, Poland). The rhodamine and uranine were used as tracers. The ^{82}Br was used as a reference substance to determine the decay rate of fluorescent dyes in river's water.

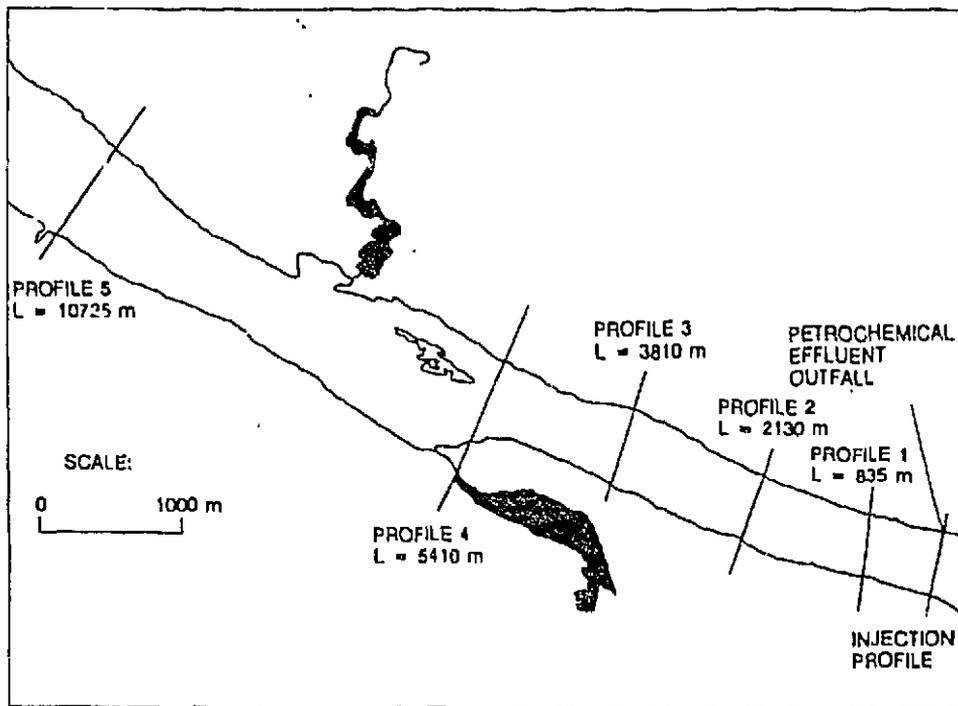


Fig.7. Measuring reach. Vistula river, Plock area (Poland).

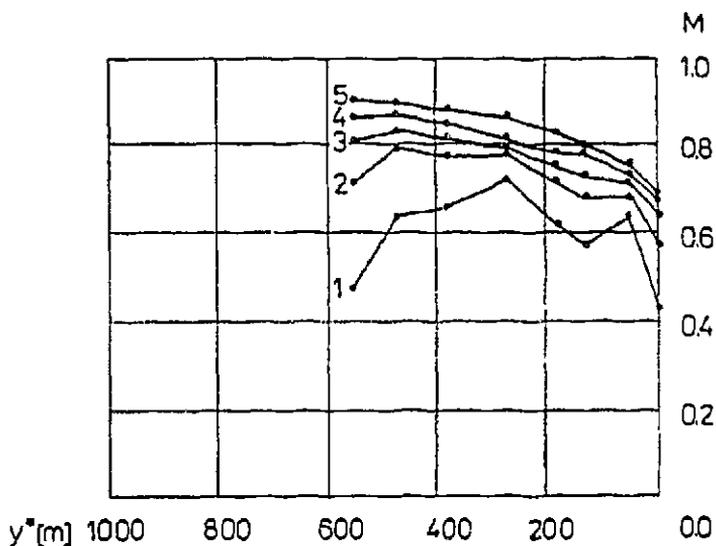


Fig.8. The values of mixing degree (M) vs. position of the discharge point on river width axis (y^*) Vistula river, Plock area (Poland). 1 - distance 835 m. 2 - distance 2130 m, 3 - distance 3810 m. 4 - distance 5410 m, 5 - distance 10725 m.

For this purpose the triple tracer experiment was performed on the river reach selected for dye tracer tests.

A series of tracer experiments was performed in order to determine the values of mixing degree at different distances downstream of the outfall for various position of discharge point on river width axis (Fig.7). The results are shown in Fig.8. The experimental data obtained correspond to medium water level which remained during the interval under investigation. This state is also typical for major part of a year.

The point distanced of 120 m of the right riverside has been accepted as optimal location of the effluent outfall. The costs of constructing the underwater pipe affected this solution. The dilution lines for actual and expected state of the pollutants dispersion have been depicted in Fig.9.

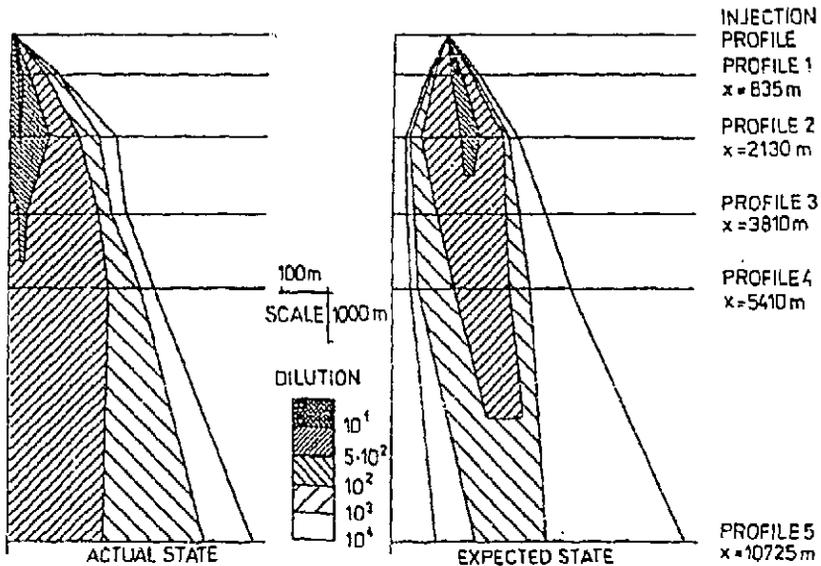
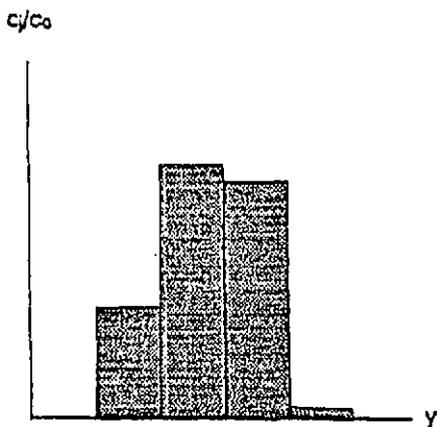
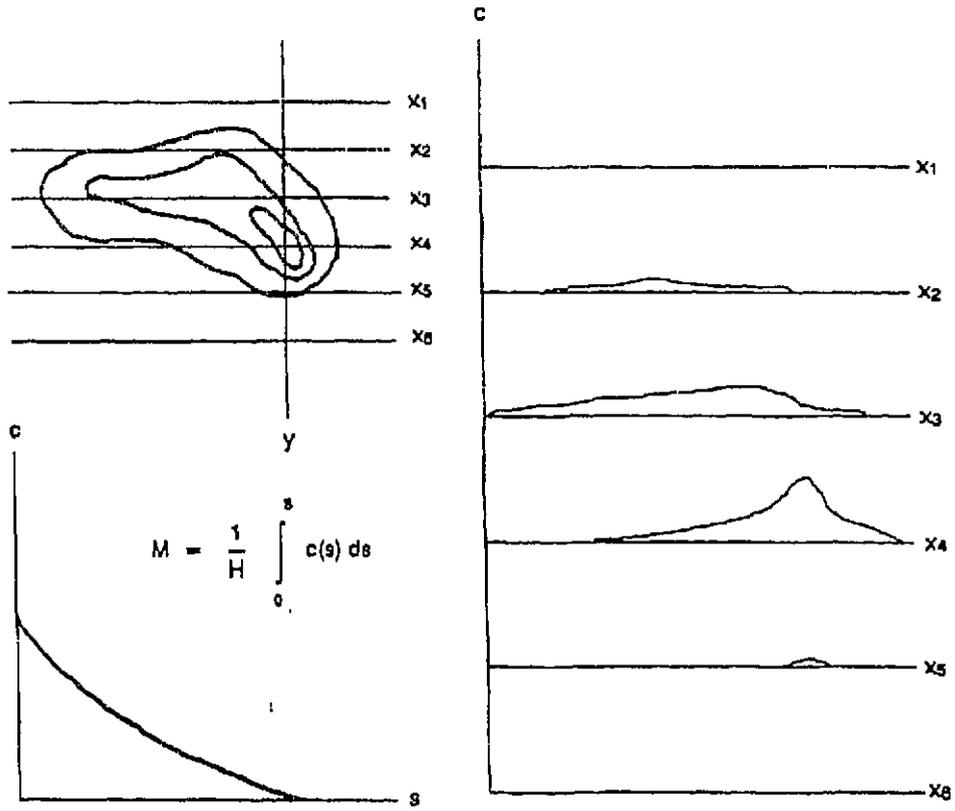


Fig.9. The dilution lines (simplified) plotted for actual and expected states of petrochemical effluent transport. Vistula river, Plock area (Poland).

Displacement of the discharge point to the optimal location will result in growth of the dilution intensity of 1.5 times. This corresponds to reduction of maximal pollutants concentration in the river water of 3.85 times at distance of 10 725 m downstream of the discharge point.

5. DILUTION OF POLLUTANTS IN BIG WATER RESERVOIRS

The method presented under 4.3. above enables to predict mixing degree values and to determine mean values of pollution degree at different distances from discharge point. In order to evaluate distribution of wastes dilution it is necessary to



$$\frac{c_i}{c_0} = \frac{1}{R_i} = \frac{Q}{uM} \int_{-s}^s c(x_i) dx_i$$

Fig.10. Diagrammatic illustration of a procedure of determining the successive values of dilution (R_i) on the basis of isoconcentration lines.

make tracer measurements. Such kind of work is done by instantaneous tracer injection using the measurement technique described under 3.3.2. above. Tracer is injected either into sewage discharged or directly into water at a point of intended sewage outfall. Tracers injected undergo identical dispersion and dilution processes as the pollutants discharged into water. Dilution of pollutants at predetermined point of natural receiver is expressed by the following equation [19]:

$$R_i = \frac{UA}{Q \int_{-\infty}^{+\infty} c(x_i) dx_i} \quad (44)$$

where:

R_i - value of dilution at i -th point of the effluent continuously discharged;

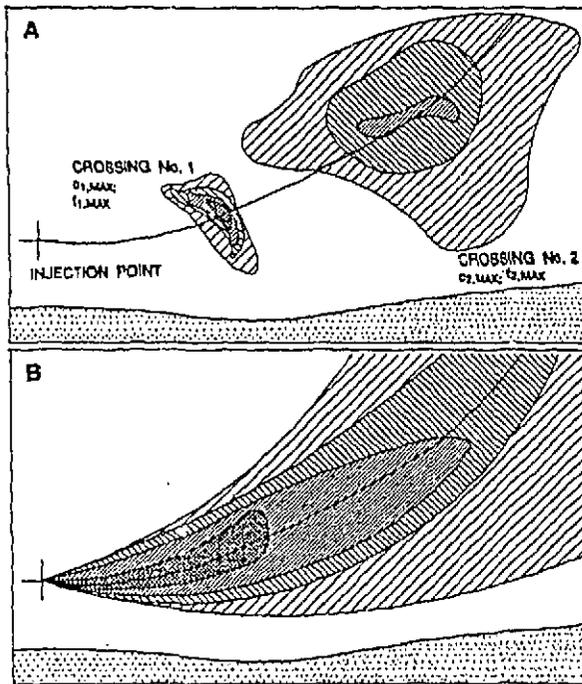
A - total amount (mass or activity) of the tracer instantaneously injected;

Q - effluent discharge rate;

u - mean transport velocity;

$c(x_i)$ - distribution of concentration of instantaneously injected tracer along the line $(0, x_i)$ parallel to direction of transport.

The knowledge of measured distributions $c(x_i)$ along multiple axes $0, x_i$ parallel to direction of transport permits to determine distributions of dilution value (R) or relative concentration of pollutants (c/c_0) along an axis optionally oriented in respect to main



direction of transport, at predetermined distance from tracer injection point. Distributions $c = f(x_i)$ are obtained on the basis of isoconcentration lines being, in turn, determined as result of tracer experiment (see under 3.2.2.). Initial quantity of tracer is calculated by measuring the surface areas confined by subsequent isoconcentration lines and by assessment of mean depth of tracer plume. The measurements are being made by means of mobile measuring stand installed aboard of the speed boat (Fig.1).

In Fig.10 a procedure of determining values of dilution along an axis perpendicular to main direction of transport is illustrated diagrammatically. Repetitive application of this procedure for successive isoconcentration lines sets leads

Fig.11. The example of isoconcentration lines (A) and respective dilution lines (B).

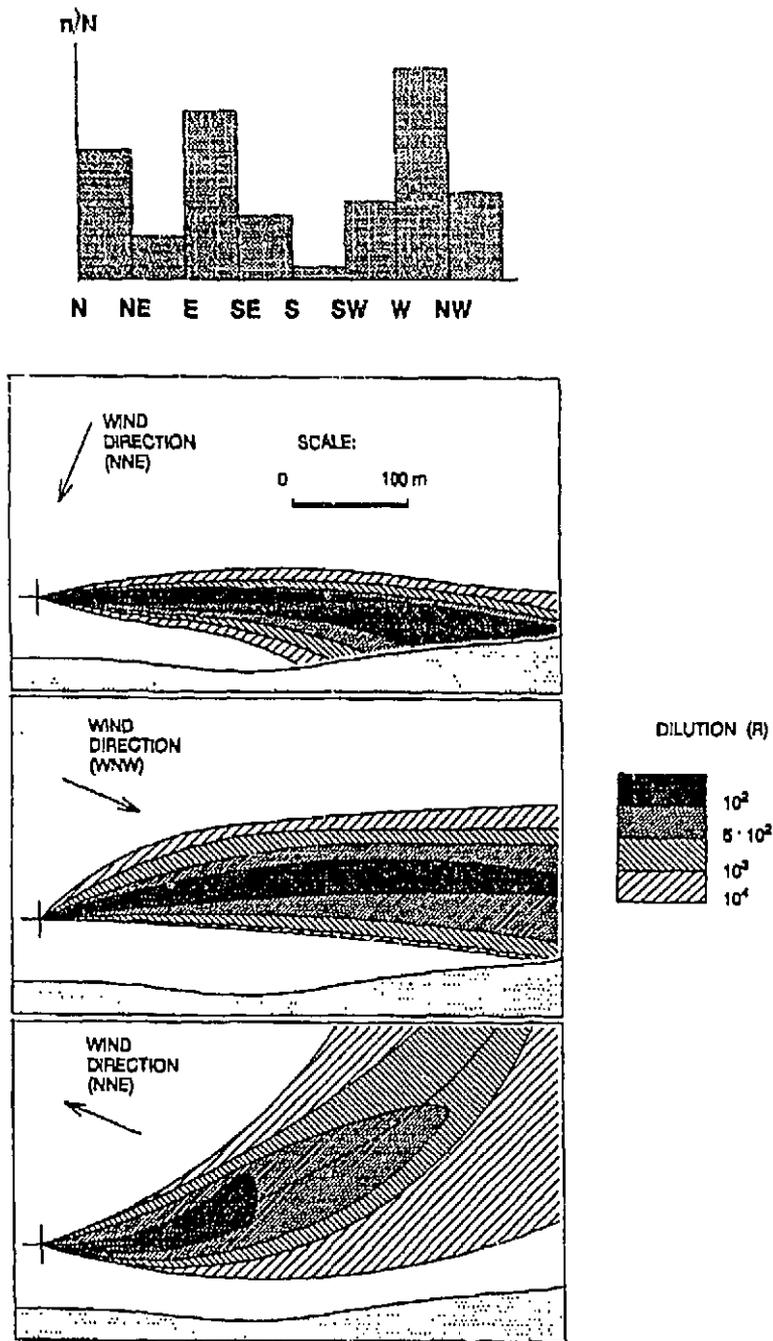


Fig.12. The histogram of frequency of predetermined wind directions and dilution lines (simplified) determined under most typical condition for the region under test (Dead Vistula, Gdańsk area, Poland).

to determination of a number of dilution curves corresponding to increasing distance from the tracer injection point. The spreading diagram constitutes a set of lines connecting points of the same dilution marked on a map of a region concerned. In Fig.11 an example of isoconcentration lines determined as result of tracer measurements and corresponding dilution lines is shown.

Fig.12 illustrates a histogram indicating frequency of predetermined wind direction appearing over a region under test of a big water reservoir and dilution lines for conditions most frequently appearing. This way of spreading prediction enables to assess a region, extent and probability of occurrence of μ . determined hazards. The method is particularly useful in selection of appropriate location for discharge of sewage into lakes and coastal sea water. Predicted concentrations of pollutants are determined on the basis of known expected values of the initial pollutant concentration (c_0) and the effluent discharge rate (Q).

6. INITIAL DILUTION PHASE FOR UNDERWATER OUTFALLS

One of stages of the pollutant transport is the initial dilution stage taking place near to discharge point. A primary mechanism observed during that stage is the interaction between a jet of wastes and ambient water. This mechanism is of particularly great importance in the case of underwater outfalls into big water reservoirs. Initial dilution depends on conditions prevailing in receiving water reservoir as well as on design characteristics and location of the outfall. Correctly designed dumping facility should ensure possible high dilution in close vicinity thereof.

While introducing into motionless water a jet of liquid, several different dilution patterns can be distinguished differing from each other, from view-point of process engineering, in the nature of dispersion. Such differences may result from a manner of introducing a waste jet into water or from substantial differences in densities between introduced jet and ambient water. For purpose of analyzing the initial spreading of effluent most interesting is the spreading of a jet being introduced horizontally through a discharge tube of circular cross-section into a medium of higher density. In this case a jet introduced undergoes the action of buoyancy force being proportional to difference in densities between jet and ambient water. Under action of buoyancy force the jet axis is deflected towards water surface. As so deflected jet moves towards water surface both its momentum and buoyancy decrease. This results in turbulent mixing at cost of gradual loss of jet's kinetic and potential energy. These events constitute essential mechanism of jet dilution. To describe and analyze the events of such kind it is then possible to use a procedure typical for description of turbulent flow of liquids, which consists in solution for a particular case the equations of continuity and conservation [23, 24]. The initial mixing stage terminates with formation of diluted waste cloud having density equal to that of ambient water (Fig.13). Further progress of spreading and dilution process depends on mixing conditions prevailing in the water reservoir.

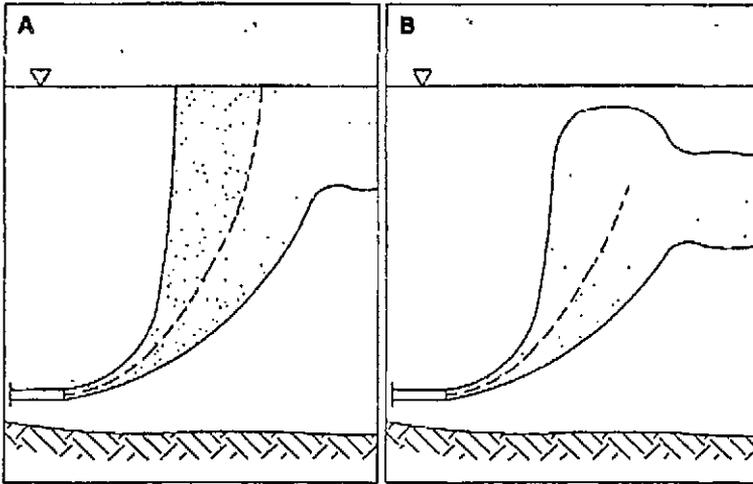


Fig.13. The examples of typical waste spreading. A - surface spreading, B - trapping.

Mathematical analysis of initial dispersion process is feasible while assuming constant density of surrounding water and basing on relationships derived empirically. These relationships indicate that dilution and linear velocity along jet axis are decreasing with increase of distance from discharge point and depends on difference in densities between stream liquid jet and diluting medium as well on diameter of discharge tube. These relationships have the following forms [25]:

$$R_m = 0.54Fr \left(\frac{z}{dFr} \right)^{7/16} \quad \text{for } \frac{z}{d} < 0.5Fr \quad (45)$$

$$R_m = 0.54Fr \left(0.38 \frac{z}{dFr} + 0.68 \right)^{5/3} \quad \text{for } \frac{z}{d} \geq 0.5Fr \quad (46)$$

$$\frac{u_0}{u_m} = 0.4Fr \left(\frac{z}{dFr} \right)^{2/11} \frac{\left[1 + 1.17 \left(\frac{z}{dFr} \right)^{4/3} \right]^{1/2}}{1.08 \left(\frac{z}{dFr} \right)^{2/3}} \quad (47)$$

where:

R_m - jet dilution at its axis;

z - depth coordinate;

d - diameter of discharge tube outlet;

u_0 - initial velocity of jet;

u_m - velocity of jet at its axis;

Fr - Froude number:

$$Fr = \frac{u_0}{\left(\frac{\rho_a - \rho_0}{\rho_a} g d \right)^{1/2}} \quad (48)$$

where:

ρ_0 - initial density of jet;

ρ_a - density of ambient water;

g - acceleration of gravity.

Although the equations (45) - (47), describe well the initial dispersion phase of introduced jet, they are of little suitability for predicting waste spreading. Natural water reservoirs only seldom can be considered as containing water of constant density. Stratification, i.e. horizontal division of water into layers of different densities, is a characteristic feature of majority of natural water reservoirs.

Difference in temperature and salinity are the factors causing such stratification. In this respect majority of natural water reservoirs are characterized by certain distribution of density over their depth. The stratification constitutes a phenomenon occurring in particularly distinct manner in sea water.

A modified procedure is being used to analyze the cases of such a nature. It assumes division of the density distribution of water, over its depth into a number of layers, each having constant density differing from that of other layers and being in fact mean density for a given layer:

$$\rho_{a,i} = \frac{\rho_{a,i} - \rho_{a,(i-1)}}{2} \quad (49)$$

In order to determine dilution of introduced jet for each of such layers the equations (45) and (46) are being used. Values obtained for $(i - 1)$ -th layer are simultaneously initial ones for the i -th one. Calculations are started from a layer situated at waste discharge level ($z_i, i = 0$) and continued stepwise layer by layer in order to determine corresponding R_m values for each of them.

In order to make such calculations the definition of Froude number has been modified as follows:

$$Fr_i = u_0 \left[\frac{i \rho_0}{g d \sum_{j=0}^i (\rho_{a,j} - \rho_0)} \right]^{1/2} \quad (50)$$

So modified Froude number is used in equations (45), (46). Consequently, a partial dilution for the given layer $z_i - z_{i-1}$ is defined by the following formula:

$$\Delta R_{m,i} = \frac{R_{m,i}}{R_{m,(i-1)}} \quad (51)$$

Dilution of a jet in its axis at z_i -th level is expressed by the product of values $\Delta R_{i,j}$ calculated for layers situated below the z_i -th level (where $j = 1, 2, \dots, i$):

$$R_{m,i} = \prod_{j=1}^i \Delta R_{m,j} \quad (52)$$

Density of liquid along jet axis at z_j -th level and its density averaged in cross-section thereof is determined by the following formulae:

$$\rho_{m,i} = \frac{[\Delta R_{m,i} - 1] \rho_{a,i} - \rho_{m,(i-1)}}{\Delta R_{m,i}} \quad (53)$$

and:

$$\rho_{m,0} = \rho_0 \quad (54)$$

$$\bar{\rho}_1 = \frac{[\beta R_{m,i} - 1] \rho_{a,i} + \rho_0}{\beta R_{m,i}} \quad (55)$$

$$\bar{\rho}_1 = \frac{[\Delta R_{m,i} - 1] \rho_{a,i} + \bar{\rho}_{i-1}}{\beta R_{m,i}} \quad (56)$$

The β in the equation (55) is a dimensionless coefficient describing the nature of concentration distribution over cross-section of a jet. As it is feasible, without making any substantial error, to assume symmetry of this distribution in respect to jet axis this value can be assumed to be $\beta = 2$.

There are two types of jet spreading (Fig.13). First of them refers to cases when density of jet being introduced never reaches that of ambient water. In such cases, wastes come out to water surface. This is a disadvantageous situation as so formed cloud of wastes undergoes still the action of buoyancy force which retards turbulent mixing in vertical direction. From the environment protection view-point much more favorable is the situation when both densities become equal to each other at some depth below water surface. In such cases the cloud of wastes is "trapped" at certain depth and then undergoes the dispersion in all directions. The procedure presented above enables both to predict the nature of spreading (surface or trapping) and to determine characteristic levels for underwater trapping.

While analyzing initial dispersion stage two parameters are being used to determine the trapping. They are: MAXI level i.e. level at which jet density along its axis becomes equal to that of ambient liquid and MIDI level i.e. level corresponding to equalization between mean density of jet over its cross-section and density of ambient liquid [26]. In the developed procedure the MAXI and MIDI levels are determined as coordinates z_j corresponding to values: $\rho_{m,i} = \rho_a$ and $\rho_i = \rho_{a,i}$ respectively.

In these cases maximum level to which a jet is elevated is lower than MAXI one and this results from the fact that jet elements are losing their kinetic energy due to work necessary to overcome gravity force. There are two kinds of elevation levels [25]: MAXO level for jet axis elements and MIDO level for elements of a jet of mean density over its cross-section. These levels are being determined by analyzing the relationships between kinetic energy of a jet on one hand and its density and density

of ambient medium on the other. Kinetic energy of a jet mass unit for a predetermined level is expressed by the following formulae:

$$K_i = \frac{u_{m,i}^2}{2} \quad (57)$$

$$\bar{K}_i = \frac{u_{m,i}^2}{2\beta'} \quad (58)$$

representing mean values of jet kinetic energy per mass unit in direction parallel to jet axis. Symmetry of velocity distribution over cross-section corresponds to a coefficient value of $\beta' = 3$. Energy balance equation for the jet elevation zone can be written as follows:

$$K_{MAXI} = \int_{z=MAXI}^{z=MAXO} g [\rho_a(z) - \rho_{m,MAXI}] dz \quad (59)$$

$$K_{MIDI} = \int_{z=MIDI}^{z=MIDO} g [\rho_a(z) - \bar{\rho}_{MAXI}] dz \quad (60)$$

Values of z coordinates corresponding to MIDO levels are determined by making use, beside of the equations (59), (60), also of the equation (47). The equations (59) and (60) are being integrated cumulatively, what remains in accordance with previously made assumption of division of the $0, z$ axis into layers of constant density. In Fig.14 an example of underwater trapping is shown with its associated characteristic levels and corresponding water and jet density distributions over the depth.

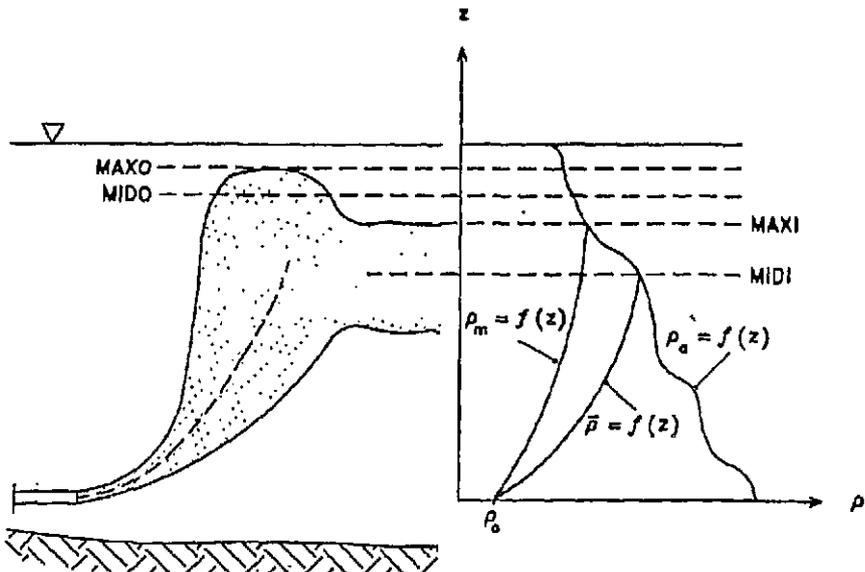


Fig.14. The characteristic levels for trapping.

Table 2. Depth distributions of density parameter of ambient water (σ_a) and respective measured and calculated values of MAXI and MIDI levels (initial value of the jet density parameter $\sigma_0 = 4.0 \text{ kg/m}^3$)

Data set no.			1	2	3	4	5	6	7
Initial jet velocity	u_0	m/s	1.9	1.9	1.9	1.9	1.1	1.1	1.1
Orifice diameter	d	m	0.115	0.115	0.115	0.115	0.15	0.15	0.15
Verticale co-ordinate	Depth	Density parameter of ambient water*							
z	h	σ_a							
m		kg/m ³							
12.0	1.0	5.4	11.3	10.0	7.0	6.2	5.2	5.1	
10.5	2.5	5.4	11.3	10.0	7.0	6.2		5.1	
7.0	5.0	5.4	11.5	10.0	7.5	6.2	5.2	5.1	
5.5	7.5	5.4	11.9	10.1	10.1	6.2		5.1	
4.0	9.0			11.1	9.3		5.2	5.2	
3.0	10.0	5.4		11.1	11.0	6.2		5.2	
2.0	11.0	5.5	12.2	11.2	11.6	7.6	5.4	5.2	
1.0	12.0	10.2	12.2	11.8		8.1		10.3	
0.0	13.0	14.1	12.2	11.9		8.3	5.6	13.6	
-1.0	14.0	14.9	12.3	11.9	12.0	9.9			
-2.0	15.0	16.2	13.3	11.9	12.6	10.3			
MAXI (depth)	measured	m	11.0	5.0	9.5	9.5	11.0	9.5	10.5
	calculated		11.6	5.0	8.8	10.0	10.8	9.5	11.3
MIDI (depth)	measured		12.3	7.5	11.0	10.5	12.5	12.0	11.5
	calculated		12.0	7.6	11.2	10.7	11.7	11.4	10.0

* In calculations the density parameter (σ) was used. The value of σ is defined as follows:

$$\sigma = 1000 \cdot (\rho - 1000)$$

where:

ρ - the density [t/m³].

The procedure presented above enables to predict values of jet dilution along its axis, mean dilution for different depths and characteristic trapping levels on the basis of known density distribution of the water along the depth of receiver and the following data: discharge tube diameter (d), expected waste discharge rate (Q) and initial density of discharged wastes (ρ_0). The procedure has been verified by comparing calculated MAXI and MIDI values with those determined experimentally (use was made of experimental data published by Harremoes [27]). Average deviation of calculated values from those being determined experimentally amounted to $\pm 0.4 \text{ m}$ for analyzed cases.

Results obtained (Table 2) indicate similar probability of positive and negative deviation occurrence. This is an evidence of statistical nature of the error. A systematic error would demonstrate itself by predominating probability of deviation with either of signs. This means that simplification being adopted while formulating the calculation procedure do not pertain to substantial extent the investigated processes.

The error of only $\pm 0.4 \text{ m}$ made while determining the characteristic levels should be considered as highly satisfactory accuracy and consistency.

7. SELF-PURIFICATION

Pollutants introduced into a natural water receivers undergo the gradual degradation due to physicochemical processes occurring in aqueous medium and its biological activity. An essential parameter in assessing degree of pollution of surface waters is the rate of pollutant degradation. The value of this parameter can be determined on the basis of radioactive tracer investigations by comparing measured distribution of the tracer concentration (having known disintegration rate defined by its half-life time) with distribution of concentration of certain pollutant determined by taking and analyzing samples of reservoir water.

Studies on possibilities of implementing this method in determining degradation rates for selected substances present in natural water reservoirs are currently carried out at the INCT. Determination of degradation rates of pollutants is based on radioactivity balances made for a radioactive tracer introduced instantaneously and mass balance for selected substances contained in wastes continuously discharged into a water receiver. The balance is made for surface layer in the reservoir. In the cases when ^{82}Br is being used as a tracer, the layer is 1 m thick which corresponds to effective layer of the ^{82}Br detection by means of submersible scintillation probe.

Quantity of pollutants transported in the surface layer is expressed by the following equation:

$$J = u \int_{-\infty}^{\infty} \hat{C}(y) dy \quad (61)$$

where:

$\hat{C}(y)$ - concentration distribution of certain pollutant along the axis perpendicular to the transport direction;

u - mean transport velocity.

The distribution $c = f(y)$ is determined on the basis of chemical analysis of samples taken along the $0, y$ axis at a predetermined distance from waste discharge point. If that pollutant does not undergo the degradation the value J from the equation (61) would be determinable on the basis of tracer isoconcentration lines:

$$J_0 = \frac{\hat{C}_0 Q}{M} \int_{-\infty}^{\infty} \int_0^{\infty} c(x, y) dx dy \quad (62)$$

where:

\hat{C}_0 - initial concentration of the certain pollutant;

c - concentration of the tracer.

The double integral in the equation (61) is equal to tracer's surface amount (M_s) and therefore:

$$J_0 = \hat{C}_0 Q \frac{M_s}{M} \quad (63)$$

Since pollutants undergo the degradation in a natural water reservoir the values J and J_0 determined from the equations (61) and (62) respectively are not equal to each

other and their ratio represents the value of relative degradation of a substance concerned:

$$E = \frac{J}{J_0} \quad (64)$$

This degradation takes place within the time $t = L/u$ (where L is a distance between waste discharge point and measurement cross-section). The degradation rate can be determined on the basis of a series of measurements of the value E for different distances from waste discharge point. The degradation rate k is being determined as a slope of the regression line $\ln E = f(t)$.

An example of evaluation of the degradation rates values is shown on Fig.15. The data presented are responded to selected components of petrochemical effluent; the oil products, phenol and chemical oxygen demand (COD). The experiments were carried out in Vistula river in Plock area (Poland).

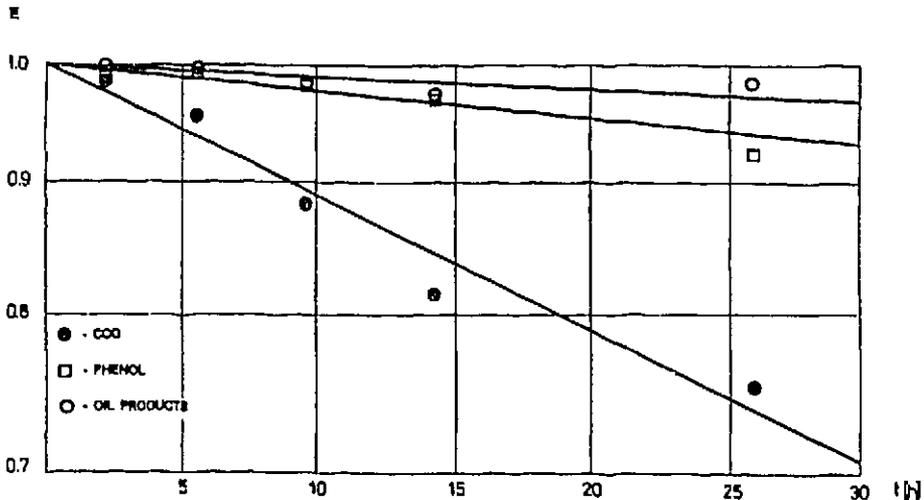


Fig.15. The values of relative decomposition (E) vs. time and respective regression lines $E = \exp(-kt)$.

The degradation rates determined in Vistula river are: $2.2 \cdot 10^{-3} \text{ h}^{-1}$ ($6.11 \cdot 10^{-7} \text{ s}^{-1}$) for phenol; $1.04 \cdot 10^{-3} \text{ h}^{-1}$ ($2.88 \cdot 10^{-7} \text{ s}^{-1}$) for oil products and $1.17 \cdot 10^{-2} \text{ h}^{-1}$ ($3.25 \cdot 10^{-6} \text{ s}^{-1}$) for the COD. This means that of about 12 % of phenol, 3 % of oil products and 26 % of COD are eliminated in the river reach under investigation (Fig.7). Moreover, the average concentrations of these pollutants at the 5-th measurement profile (distance 10 725 m) are 167 time lower than their initial concentrations. That is the evidence of the multiplex preponderance of the dispersion processes over the selfpurification at the early stage of dilution preceding the pollutant concentration homogenization within the river cross-section. According to relations presented in Fig.15 the selfpurification become the major effect for the transport time of order of several hundred hours. As only the pollutant concentration becomes homogeneous within the river cross-section the selfpurification commences to be the only mechanism governing further diminishing the pollutant concentration till elimination of the pollutions from the environment.

8. SUMMARY AND CONCLUSIONS

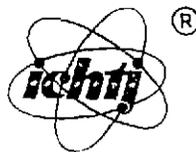
The tracer introduced into the natural receiver is subject of the same actions as the effluent discharged. This is the cause why the data related to the transport and dispersion of effluent obtained by using the tracer method may be considered as the most reliable ones. For this reason the tracer methods constitute a convenient source of information about processes taking place during transport of pollutants in surface waters. Their main advantage is, beside of possibility of using them for assessment of water pollution degree, the fact that they allow to predict all stages of the spreading process. A possibility of using them to predict regions, magnitude and probability of possible occurrence of predetermined hazards makes these methods particularly useful in selecting appropriate location of the prospective waste water outfalls and studying the self-purification processes of natural water receivers.

The methods presented constitute a part of INCT's 20 years experience in application of tracers and isotopes for studying questions related to the environment protection. Actually the all techniques described can be commercially used to solve certain practical problems.

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