LONGITUDINAL PULSATIONS OF THE FLOW VELOCITY AND THE WATER TURBULENCE IN THE LOWER DANUBE RIVER

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Abstract. The hydrometrical database containing the data recorded on the River Danube in 1978-1997 period by the National Institute of Meteorology and Hydrology with author's participation was processed. On this base were obtained the empirical functions of the kinematics of the water flow and of the water turbulence (duration of mixing, length of mixing and turbulence diffusion coefficient). The author's contribution consisted in the organisation and carrying out the field research, in database structuring and field data filling into it, in data processing and mathematical modelling of the hydraulic turbulence.

Résumé. Ont a utilisé la base de données hydrométriques accumulées par des mésures effectuées dans la nature sur le fleuve Danube par l'Institut National de Météorologie et Hydrologie pendant les années 1978-1997. Par l'usinage des données de mesures, ont a obtenu les fonctions empiriques de la cinématique de courant d'eau (la durée de la voie de mélange, la longueur de la voie de mélange et le coefficient de diffusion turbulente). La présente publication a comme objet de présentation les résultats usinés. La contribution de l'auteur consiste en l'organisation et la réalisation des mesures dans la nature, en l'usinage des mésures et en modélisation des processus hydrauliques de turbulence.

Key words: kinematic water current, empiric functions, mathematical modelling, turbulence hydraulic processes, duration of mixing way, length of mixing way, turbulence diffusion coefficient, Danube riverbed

1. GENERAL SETTING

During the hydrological research carried out in 1978-1997 period within the Lower Danube, the attention was drawn on the kinematic structure of the water flow for finding the parameters of empirical functions describing the flow and mixing processes. The knowledge of the flow turbulence is of basic importance: the turbulence is responsible for the exchanges among different water layers, for the energy and heat transfer, for velocity pulsations, etc. The turbulence has a significant environmental impact, as it results in mixing of the water masses, suspension of solid particles and water oxygenation and purification.

The author has contributed to the organisation and implementation of the research on flow turbulence within the Lower Danube River, between Bazias (km 1072) and the river mouth zone into the Black Sea (km 0). The studies and the field measurements have been carried out in a number of hydrometrical cross-sections, on which, at the same time, samples of water and sediments have been taken for obtaining indications on water and sediment quality.

The research was focused on the following aspects:

- Field measurements of the horizontal components of the flow velocity pulsations within the Lower Danube;
- Determination of the main statistical characteristics of the flow velocity and turbulence within the measurement stations (time average velocity, standard deviation of velocity values, coefficient of time variation of the velocity, also called degree of current turbulence, the asymmetry of velocity values, the duration of mixing, the length of mixing and the coefficient of turbulent exchange in the water mass).

The field measurements of flow velocity and turbulence have been carried out with the micro-current-meter GR99 (made by Gidrometpribor, Russia). The micro-current-meter has an integrator of the impulses generated by each rotation of the propeller.

In every measurement point 150 flow velocity measurements at 2 seconds interval have been carried out (the total duration of a single measurement session was 300 seconds). The measurements have been carried out on the vertical of the considered station at 6 levels, starting at the surface (about 0.1 m bellow the water mirror), at 0.2, 0.4, 0.6, 0.8 of the total depth and at the bottom (at about 50 cm above the bottom). On each cross-section three recording verticals placed two at both banks and one of the middle of the section were considered. All the recorded values were stored on magnetic support. For a single vertical 7 ASCII files have been created: the first was dedicated to the cross-section and vertical station location and water depth, the date and time of measurement, the current-meter calibration parameters; the other 6 files contain the recorded velocity values at the six depth levels mentioned above.

During 1978-1997 period 138 verticals for measuring flow longitudinal pulsations have been carried out. The verticals were located along the Romanian section of the River Danube as follows: 5 at Bazias (km 1072), 6 at Orsova (km 957), 2 at Turnu Severin (km 931), 17 at Bechet (km 678.7), 19 at Turnu

Măgurele (km 596.3), 17 at Giurgiu (km 493), 13 at Chiciu-Călărasi (km 379.6), 13 at Vadu Oii (km 238), 21 at Ceatal Izmail (km 80) and 28 on the main distributaries of the Danube Delta (Kilia, Tulcea, Sulina and St. Georges), especially at their mouth at the Black Sea (km 0).

The soft for processing the field measurements data has been written in Q-Basic (Bondar, unpublished data). The following parameters have been calculated from the current velocity data. For processing, the depth axis (z) was considered oriented from the water surface to the bottom.
The time average velocities (ui) of the water current on the time interval (dt) of 2 seconds expressed in m/s for i=1, 150.
The time average velocity (uz) on the entire recording duration in the layer of depth (z), expressed in m/s,

$$uz = \frac{\sum_{i=1}^{i=n} ui}{n} \qquad (1)$$

The velocity pulsations (duzi) expressed in m/s,

duzi=ui-uz (2)

The standard deviations of velocities (σuz) expressed in m/s,

$$\sigma uz = \sqrt{\frac{\sum_{i=1}^{i=n} (duzi)^2}{n}} \qquad (3)$$

The variation coefficient of velocities (cvuz),

cvuz=σuz/uz (4)

The asymmetric coefficient of velocity (csuz),

$$csuz = \frac{\sum_{i=1}^{i=n} (duzi)^3}{n.\sigma uz^3} \qquad (5)$$

The turbulence change coefficient (μz), expressed in $kg.s/m^2$,

μz= - γa.i.z/duz/dz (6)

The informational entropy (Ez).

Ez=log(uz/0,8/σuz) (7)

For exemplifying the pulsative regime of the River Danube flow, the Fig. 1 a-f and Fig. 2 a-f represent the graphs of the variation of the time average velocity (ui) and of the linear tendency function (T), in two cross-sections situated at Bazias (km 1072) and at the Danube Delta apex (km 80). It is obvious that the Danube flow velocity pulsations are random.

2. WATER VELOCITY VARIATION WITH THE DEPTH

A number of mathematical functions expressing the vertical variation of the velocity within the water flow in natural channels is given by the specific literature (Mateescu, 1963; Loitianskyi, 1987 etc.). Depending of the type of turbulent mixing coefficient from the equation (6), logarithmic (mostly), but also elliptic or parabolic functions describing the vertical distribution of the velocity have been defined. For the River Danube, using the dynamic equation of the longitudinal motion and the equation (6), the vertical variation of the turbulent mixing coefficient was pointed out. Within the equation (6) the symbols have the following meaning:
γa - specific weight of water, expressed in $kg.m^{-3}$;
i - the water mirror slope;
z - depth of the water in m;
dz - the depth difference between water layers, in m;
du - the difference of velocities for water layers situated at dz vertical distance, in $m.s^{-1}$.
The experimental data showed that this coefficient is zero at water surface and at the bottom; its variation is follows a curve with a maximum situated in the lower half of the total water depth. By integration of the differential equation (6) it results that the function, which expresses the vertical variation of the velocity in the water flow, is of parabola power type of following form:

$$uz = auz.(1-z/h)^{buz} \qquad (8)$$

where, uz is the average velocity of the water layer at the depth z, h - the total depth of the water flow and auz and buz - parameters measured experimentally.
By averaging the function (8) for a vertical of the station we can obtain the expression of the average velocity for the entire depth h:

um = auz/(1+buz) (9)

The parameter (auz) in the functions (8) and (9) characterises the current velocity at the water surface, while (buz) depends directly of the ratio between the water surface velocity (u_0) and the average velocity for the considered vertical, as shown by the function (10):

$$buz = 1 - u_0/um \qquad (10)$$

Within the River Danube it was empirically shown that the parameter buz depends of water surface velocity and of the total depth of the flow, h:

$$buz = 0.0807 \cdot u_0^{0.788} \cdot h^{0.212} \qquad (11)$$

The function (11) is particularly useful for finding the average velocity and the vertical velocity variation, as in the field only the velocity at the water surface and total depth of the flow can be measured.

3. VELOCITY PULSATIONS

There is an extensive literature concerning the turbulence of the water flow, its theoretical aspects and

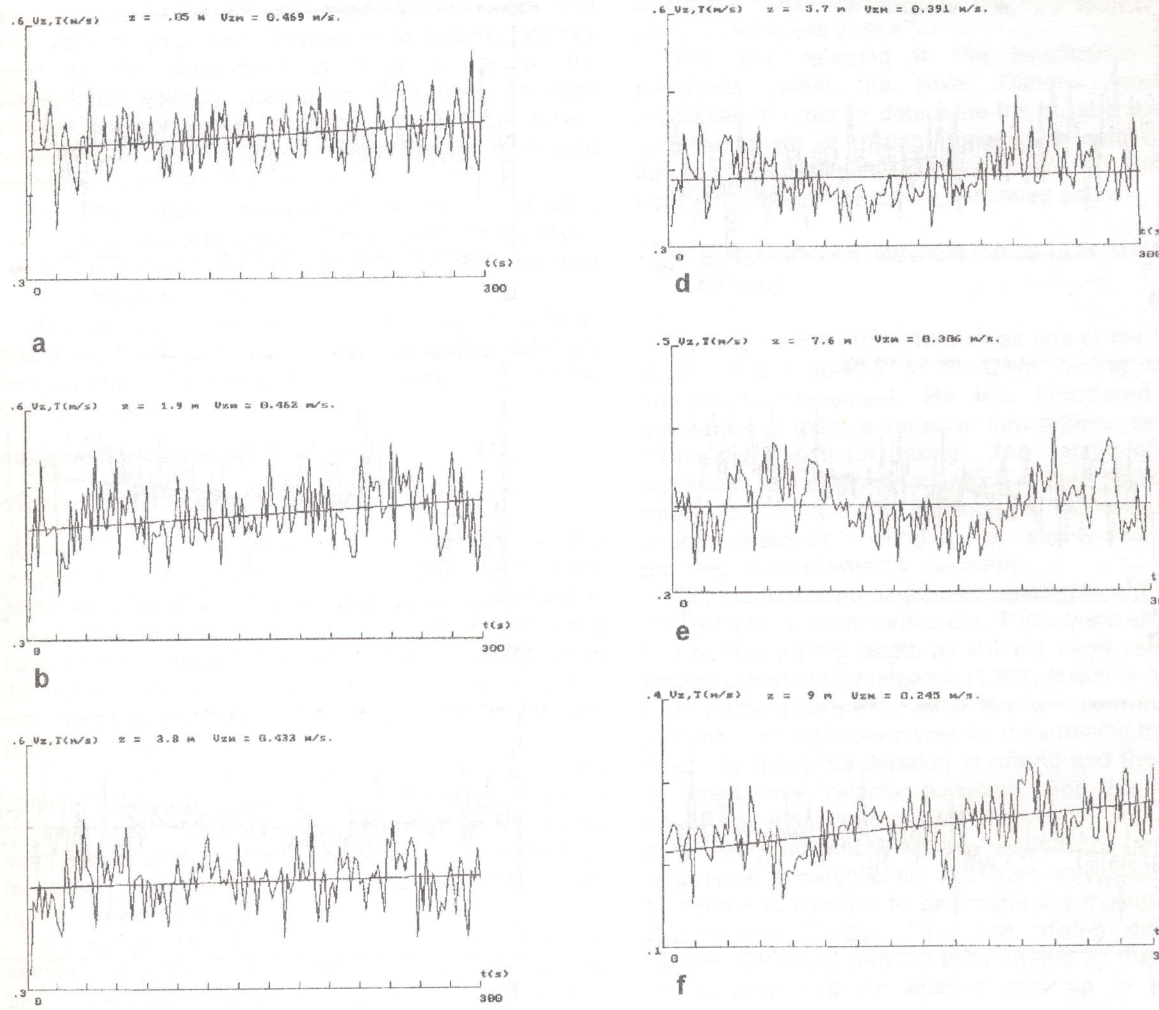

Fig. 1a-f The graphs of the autocorelations functions of the longitudinal velocity pulsation in the water layers from the central vertical of the Danube riverbed from hydrometrical section Bazias (km 1072) at the date 09.10.1997.

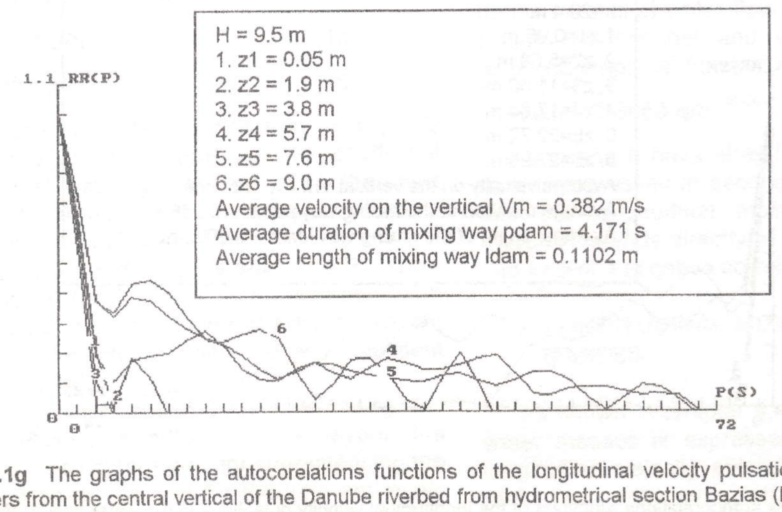

Fig.1g The graphs of the autocorelations functions of the longitudinal velocity pulsation in the water layers from the central vertical of the Danube riverbed from hydrometrical section Bazias (km 1072) at the date 09.10.1997.

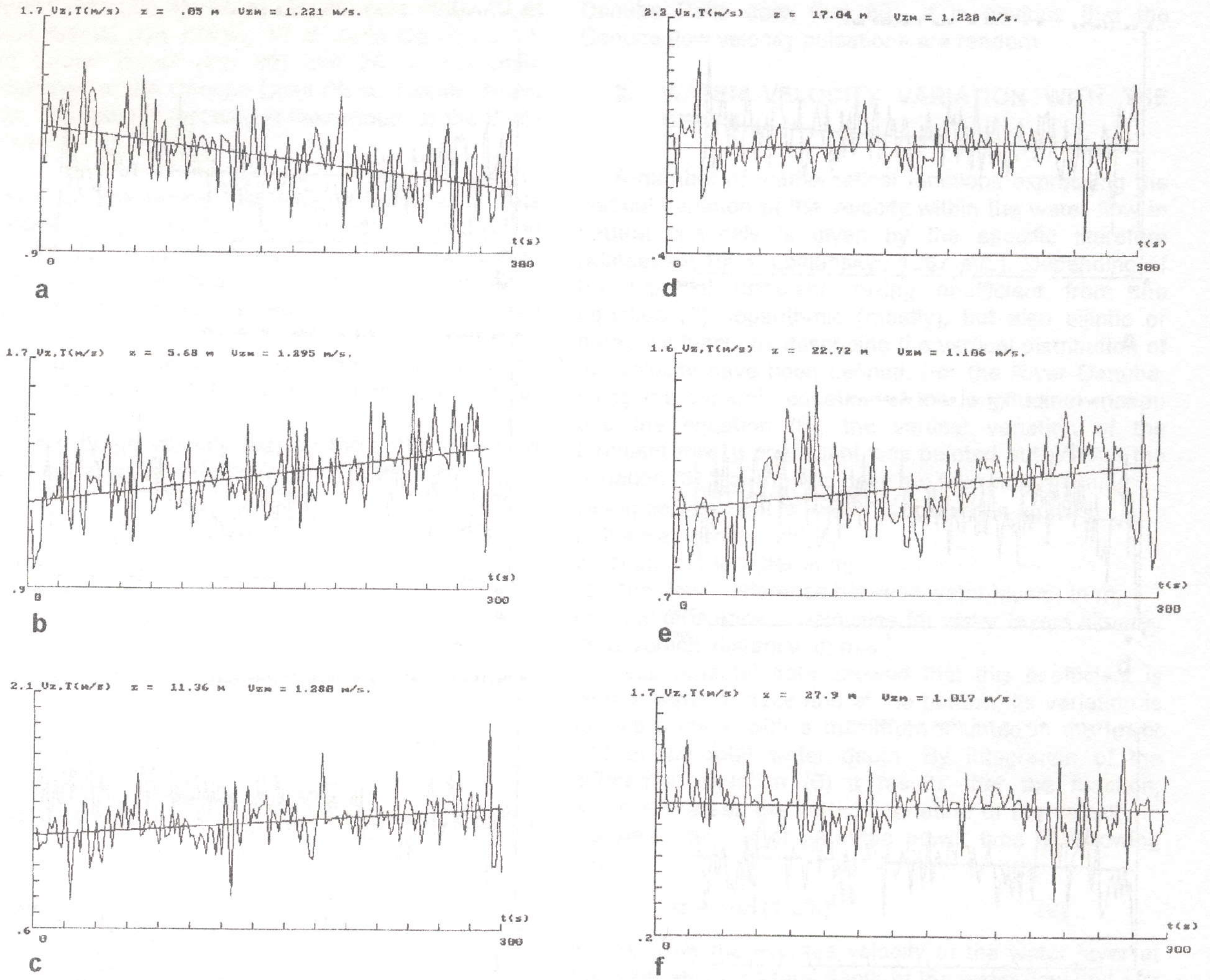

Fig 2a-f The graphics of the time variation of the water current velocity (Vz) and of the linear tendency (T) in diverse layers with depth (z) from central vertical of the Danube riverbed at Ceatal Ismail (km 80) in date of 24.04.1993. The depth in vertical h=28.4 m, the average vertical velocity Vh=1.196 m/s.

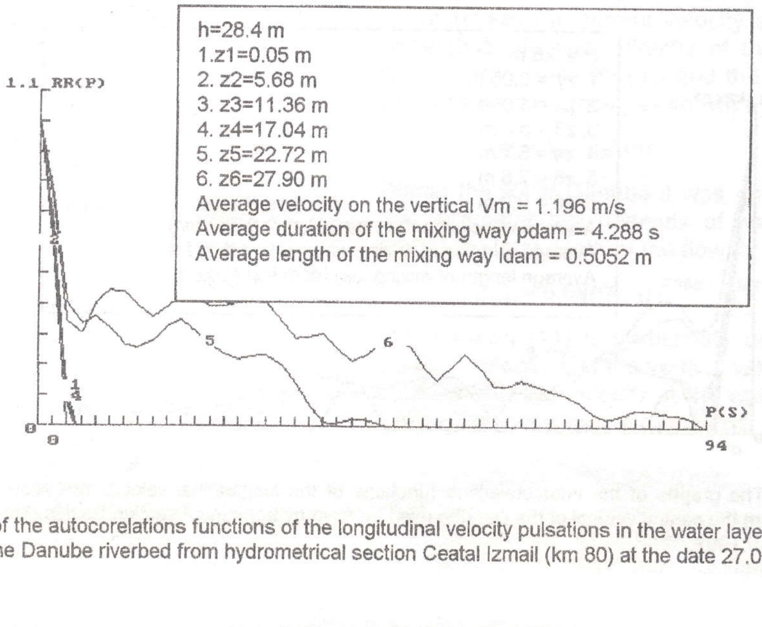

Fig. 2g The graphs of the autocorelations functions of the longitudinal velocity pulsations in the water layers from the central vertical of the Danube riverbed from hydrometrical section Ceatal Izmail (km 80) at the date 27.041993.

quantification of the process generated by short term flow velocity variations. Numerous laboratory studies used specific equipment in order to reveal tri-dimensional velocity pulsations. The obtained data allowed the experimental determination of the turbulent movement structure and its statistical analysis. Among the main results of these studies are:

- the random character of the velocity pulsation components within different layers of the flow;
- the increasing intensity of the turbulence with the water depth.

According to the Minski's laboratory experiments (in Mateescu, 1963), the distribution of turbulence intensity on the vertical of the water flow can be expressed by the following empirical functions:

$$\sigma uz/uz = 0.03353.\exp(1.63656.z/h) \quad (12)$$

$$\sigma vz/uz = 0.05188.(z/h)^{0.2373}.\exp(0.4912.z/h) \quad (13)$$

where: σuz is the square time average of the longitudinal velocity pulsations in the water layer at the depth z; uz - the time average of the longitudinal velocity in the water layer at the depth z; σvz - the square time average of the vertical velocity pulsations in the water layer at the depth z; z - the depth of the considered water layer, from the surface towards the bottom; h - the total depth of the water flow.

The laboratory research and the processing of the obtained data showed a linear statistic correlation between the longitudinal (horizontal) and vertical components of the velocity pulsations. This correlation is tighter in the bottom layers and less tight in the upper, surface layers.

As within the Lower Danube River only the longitudinal components of the velocity pulsations have been measured, it was possible to verify the function (12) only. The field measurements allowed the establishment of the parameters for this function and these parameters depend of the flow regime. Thus, if for the River Danube the function (12) has the following structure:

$$cvuz = acv.\exp(bcv.z/h) \quad (14)$$

then the parameters acv and bcv are:

$$acv = 0.067573.q/h^{0.79} \quad (15)$$

$$bcv = 0.48035.q/h^{0.8627} \quad (16)$$

where q is the specific water discharge in $m^2.s^{-1}$, h is the local depth and cvuz is the time variation coefficient of the longitudinal velocity. In this case the cvuz coefficient gives the intensity of turbulence, in the same way as in the functions (12) and (13).

The functions (14) and (15), as well as (13), show that the intensity of the flow turbulence increases with the depth of the water layers, being directly dependent of the specific water discharge and inversely dependent of the local water depth.

Additionally to the function (13), expressing the intensity of turbulence in different water layers, the function (17) has been determined for characterising the mean magnitude on the vertical for the time arithmetic average of the velocity longitudinal pulsations:

$$vph = 0.067656.q/h^{0.9606} \quad (17)$$

where the mean pulsation of the longitudinal velocity (vph) is expressed in $m.s^{-1}$.

The data referring to the longitudinal velocity pulsations within the River Danube have been processed in order to determine the duration of mixing and the length of mixing. Finally the semi-empirical function of the turbulent diffusion coefficient have been obtained. These aspects are described below.

4. DURATION OF WATER MASS LONGITUDINAL MIXING

Ludwig Prandl (1875-1955) was one of the first who studied the problems of turbulent mixing of water masses in movement. He has introduced in the mechanics of fluids a series of new notions as "way of mixing" or "length of mixing". The "length of mixing" represents the distance on which a fluid particle must roam for completely loosing its initial kinematic characteristics as the longitudinal velocity changes with the magnitude of velocity pulsation.

Up to present no direct measurements of the length of mixing have been carried out. There were attempts to find out the mixing length by indirect ways using semi-empirical methods. Mateescu (1963) presents a number of characteristics of the water flow turbulent movement statistics. He indicates a way for determining the mixing length by using the duration of mixing and the average of longitudinal velocity pulsation. For this purpose, based on measurements of the longitudinal velocity pulsations, the autocorrelative function of the velocity pulsations is established and from the graph of this function it is possible to determine the mixing duration (Fig.1g and Fig.2g). Thus the mixing duration is numerically equal with the area limited by the graph of the function and the absciss axis up to their first intersection.

The field measurements on the River Danube and these data processing show that the values of mixing duration at different water depth are random. However, a certain tendency curve can be defined, with smaller values in the water surface and bottom layers, while the larger values are within the lower half of the water flow. The average of the longitudinal mixing duration (dam) on the vertical of water flow depends of the flow regime trough the channel and can be expressed by the following empirical function:

$$dam = 7.8663.q/h^{1.0604} \quad (18)$$

where q and h have already mentioned meanings and dam is expressed in seconds. The function (18) shows that the longitudinal mixing duration of the water masses depends directly of the specific water discharge and shows a negative correlation with water depth.

5. LONGITUDINAL MIXING WAY OF THE WATER MASSES

As shown in chapter 4, the length of mixing way of water masses is expressed by the average value of longitudinal velocity pulsation in different water layers multiplied by the mixing duration for the water masses from the considered layers. Similarly to the mixing duration the mixing length has a pronounced random character on the vertical of the flow, the tendency curve showing larger values in its upper half of the water flow. The average of the mixing length (ldam) on the vertical depends of the flow regime and is expressed by the function:

$$\mathbf{ldam = 0.38501.q/h^{0.9627}} \quad (19)$$

where q and h have the same meanings as above and ldam is expressed in m.

6. THE COEFFICIENT OF TURBULENT DIFFUSION

The turbulence of fluid flows generates transverse movements (vertical and lateral) on the longitudinal flow direction, resulting in the mixing of water masses from different layers.

The turbulent diffusion is characterised by the coefficient of turbulent diffusion, which has the same dimensions as the coefficient of kinematic viscosity (square of a length reported to the time). Direct experimental measuring of this coefficient have not been done yet. For determining the diffusion coefficient a semi-empirical method has been used. This method uses the length of mixing and the time average of flow velocity. Thus on the basis of the equality between the friction strength among the layers due to the turbulent viscosity and the friction strength due to the cross-changes of the movement quantity, the coefficient of turbulent diffusion (vz) is given by the equation:

$$\nu z = \mathbf{ldamz^2.|du/dz|} \quad (20)$$

Taking into account the function (8),

$$\mathbf{|du/dz| = -auz.buz/h.(1-z/h)^{(buz-1)}} \quad (21)$$

(ldamz) is the value of the length of mixing and (vz) the coefficient of turbulent diffusion for a layer at the depth z.

The coefficient of turbulent diffusion also shows random values, with the tendency of increasing with depth. The average of the coefficient of turbulent diffusion (vm) on the vertical of a station depends of water flow regime and is expressed by the empirical function;

$$\nu m = \mathbf{0.01259.q/h^{1.1602}} \quad (22)$$

where q and h have the same meaning as above and vm is measured in $m^2.s^{-1}$.

The figures 1g and 2g represent the graphs of the autocorrelation functions for the velocity pulsations within the River Danube at Bazias (km 1072) and at the Danube Delta apex (km 80). The legends of the figures specify that Z is the depth of the water layer where the measurements have been carried out and h is the total depth of the water at the vertical of the station.

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