A case study of longitudinal dispersion in small lowland rivers

Alexander N. Sukhodolov, Vladimir I. Nikora, Paweł M. Rowiński, Włodzimerz Czernuszenko

ABSTRACT: Contaminant transport in natural streams is considered on the basis of tracer studies in Moldovian small lowland rivers. Theories describing the spread of conservative and passive pollutants in the context of a longitudinal dispersion model, as well as attempts to estimate the discrepancy between this model and natural processes, are discussed. It is shown that the model agrees with experimental data, with an accuracy ranging from 15 to 20%, at least in the upper [$\bar{C}(t) > 0.5C_{max}$] concentration distributions. The process behaves in a quasi-Fickian manner only at distances greater than 80 to 100 times the river width. Primarily, the nonuniformity of the average velocities over cross sections affects the process. An estimate of the Lagrangian spatial scales was proposed, and it was shown that those scales are as large as two to four times the length of alternate bars. *Water Environ. Res.*, **69**, 1246 (1997).

KEYWORDS: concentration distribution, Lagrangian scales, longitudinal dispersion, pollutant transport, similarity, tracer studies, modeling.

The problem of spreading pollution in rivers attracts the worldwide interest of many researchers, environmentalists, and engineers. The cheapest and most efficient way to approach these problems is through the development of suitable mathematical models derived from hydrodynamics principles. Numerous such models have been proposed (Czernuszenko, 1990, and Rutherford, 1994), but when applied to natural rivers they often do not describe the phenomenon adequately. Therefore, questions regarding the applicability of the models are of primary importance and can only be clarified with the help of field data.

In this view, we performed a number of experiments on small lowland Moldovian rivers, with the goal of describing pollutant spread using simple one-dimensional models.

It should also be emphasized that 80% of the population of Moldova lives within small-river watersheds, where living standards depend greatly on water quality in local rivers. Therefore, the development of simple methods to quantify the ability of small rivers to disperse passive pollutants, especially in cases of accidental releases, is an important task.

Methods

Longitudinal Dispersion Model. The simplest and probably most often used model in engineering practice is the longitudinal dispersion model first proposed by Taylor (1954) and still often applied (Beltaos, 1980; Day, 1975; Elder, 1959; Fischer, 1966; Vuksanovic *et al.*, 1996; and West and Mangat, 1986). With the use of a number of simplifications and averaging procedures, such a model can also be deduced from a complete three-dimensional Eulerian dispersion equation for turbulent flow (Sayre, 1975). These procedures, however, limit this model, especially when it is applied to natural streams.

Longitudinal dispersion combines two fundamental mixing processes, turbulent diffusion and advection, in open channels and is often presented in a Fickian-type form:

$$\frac{\partial \bar{C}}{\partial t} + U\frac{\partial \bar{C}}{\partial x} = \frac{\partial}{\partial x}D\frac{\partial \bar{C}}{\partial x} \qquad (1)$$

Where

$\bar{C}$ = cross-sectionally averaged concentration, kg/m^3 or g/L;
t and x = time (seconds) and distance (m) from the point of release;
U = flow-averaged velocity, m/s; and
D = coefficient of longitudinal dispersion, m^2/s.

The solution of Equation 1 for an instantaneous injection over the cross section at $x = 0$ and $t = 0$ is as follows (Fischer, 1966):

$$\bar{C} = \frac{M}{2A\sqrt{\pi D t}} \operatorname{Exp}\left[-\frac{(x - Ut)^2}{4Dt}\right] \qquad (2)$$

Where

M = mass of tracer, kg; and
A = cross-sectional area, m^2.

The main advantage of this model is its simplicity. However, several researchers revealed some effects that raised questions about using Equation 1 to describe the dispersion process in natural streams:

- Quicker decrease of the concentration maximum than follows from Equation 1 (Day, 1975);
- Nonlinear growth of the concentration distribution variance and dependence of D on time (Day, 1975); and
- Concentration distribution asymmetry at sufficiently long distances from the injection site (Nordin and Troutman, 1980).

The manifestation of these effects is different for various waterways. Violations of dispersion process laws, which follow from Equation 1, are explained by the influence of the laminar sublayer (Elder, 1959), the channel's irregular geometry producing dead zones (Valentine and Wood, 1979), the form of velocity profile (Fischer, 1966), and imperfect measuring techniques.

Experimental data on longitudinal dispersion in rivers are limited and do not cover hydraulic and morphometric conditions properly. A purpose of this study was to fill this information gap and present basic problems concerning the applicability of the longitudinal dispersion model.

Field Experiments. Tracer experiments were carried out dur-

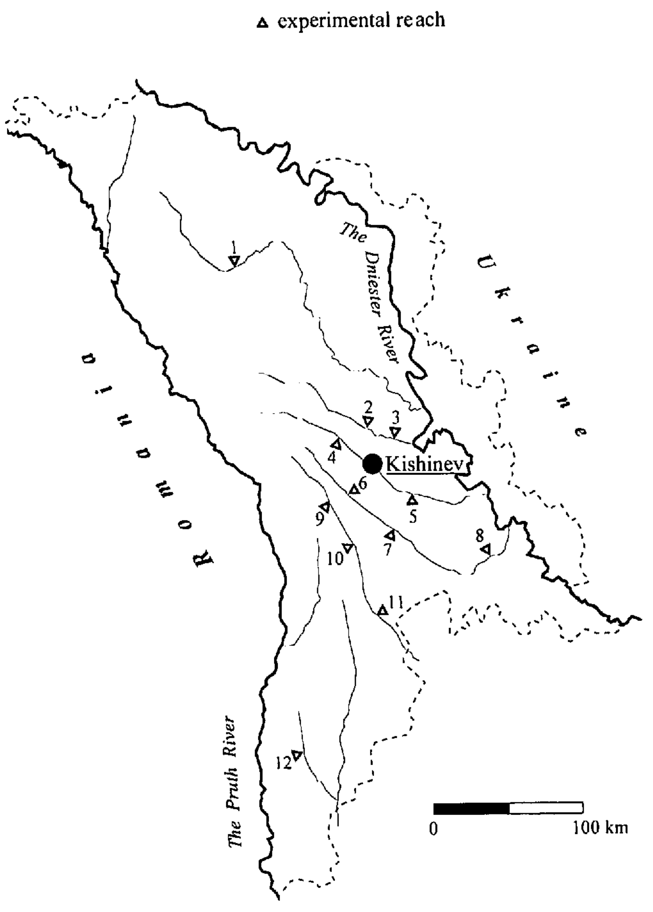

Figure 1—Locations of experimental reaches on territory of Moldova Republic.

ing 1991 and 1992 in 12 representative reaches of small lowland Moldovian rivers, as shown in Figure 1 (Nikora and Sukhodolov, 1993). The experiments included observation of the downstream changes of the instantaneously injected tracer cloud and a set of hydrometric and morphometric measurements in the river reaches. The concentrations of the tracer, flow rate, water temperature, and cross-sectional and longitudinal profiles of bed elevations were measured in each experiment. The tracer used was a solution of sodium chloride (NaCl). The volumes of the injected tracer ranged from 30 to 3 000 L, depending on the natural water mineralization and the discharge in a river. An original technique was developed to inject the tracer. A plastic flexible tube (3 m in diameter, 15 m long) was used for preparation of up to 5 000 L of the tracer solution. One of the ends of the tube was used as an injector. Because of its large diameter, the volume of the solution (30 to 3 000 L) was injected into the flow within 5 to 20 seconds. Taking into account the small river widths (2 to 11 m) and the movement of the injector across the stream, the concentration distribution obtained in the vicinity of the injection site was very homogeneous.

The concentrations of the tracer cloud were determined using conductometers (ELWRO, Poland). The quality of the tracer experiments was verified with the help of the accuracy index, $[M - Q \int C(t)\, dt]/M$ (where Q is the water discharge in cubic metres per second), which was less than 0.12 in every case. The number of the measured cross sections at which the observations of concentration were collected for one injection ranged from two to five. Examples of concentration distributions are shown in Figure 2, where C_0 is the tracer concentration at $x = 0$ and $t = 0$ and δ_t is the duration of release in seconds. The tracer concentration C_0 equaled 200 g/L in almost every case, except for the experiment in the Byk River at Tsintseren, in which it was 267 g/L. Despite large initial concentrations, it can be reasonably assumed that the density effects become negligible very quickly.

Using collected data, we estimated the widths, cross-sectionally averaged velocities and depths, shear velocities, large-scale bed-forms dimensions, and main statistical parameters of the measured tracer clouds. Details about their estimation follow.

All of the selected river reaches were characterized by a low sinuosity, an absence of tributaries, and a high level of homogeneity of channel forms. The morphometric and hydraulic characteristics of the investigated reaches are presented in Table 1. The values of flow, width, depth, velocity, and shear stress in Table 1 were obtained by averaging along experimental reaches. The variability of these parameters did not exceed 30%, except for in experiments done in the Salchea River (at Lucheshť), the Kogilnik River (at Bogdanovka), and the Botna River (at Khoresht), in which the variability of the widths and depths slightly exceeded 40%.

Experimental Results and Discussion

Propagation Velocity of the Tracer Cloud. One of the basic assumptions of the longitudinal dispersion model is that the velocity of the peak concentration propagation, U_p, is equal to the cross-sectionally averaged velocity, U_c (Fischer, 1966, and Taylor, 1954). In the present study, this assumption was tested by comparing the data from tracer experiments with hydrometric measurements. These measurements were collected with a standard propeller current meter with a small propeller, 25 mm in diameter. The comparison between U_c and U_p in the form of a bar diagram is presented in Figure 3 [n is the number of occurrences of the particular values of $(U_p - U_c)/U_p$ in the

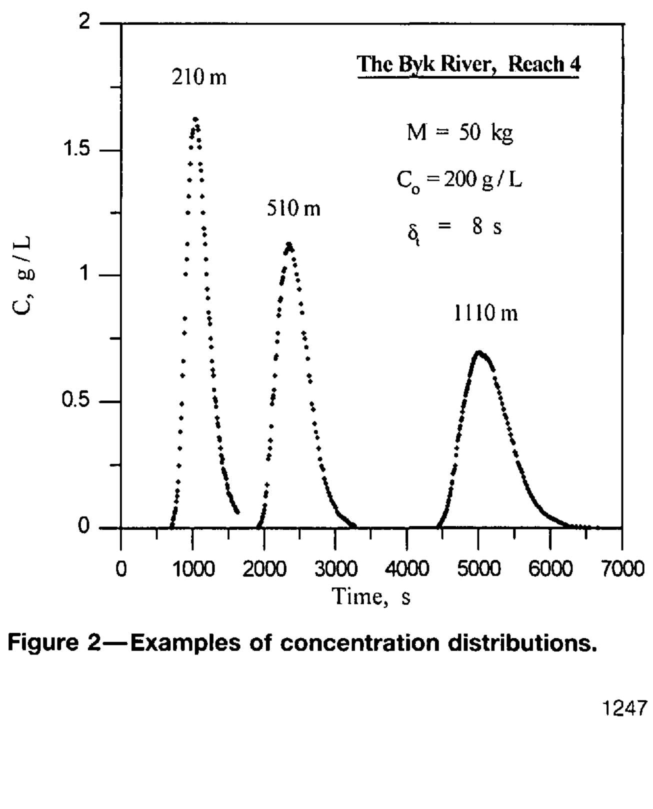

Figure 2—Examples of concentration distributions.

Table 1—Hydraulic and morphometric characteristics of experimental river reaches.

Reach number	River (location)	Q,[a] m^3/s	B,[b] m	h,[c] m	U,[d] m/s	$\sqrt{ghS}$,[e] cm/s
1	Reut (Belts)	1.15	7.1	0.41	0.40	5.2
2	Ikel (Dreslechen)	0.113	7.3	0.11	0.14	2.4
3	Ikel (Goyan)	0.087	7.1	0.31	0.04	1.4
4	Byk (Kelerash)	0.076	2.6	0.14	0.22	3.4
5	Byk (Tsintseren)	4.70	11.4	0.69	0.60	5.9
6	Botna (R. Noy)	0.046	2.1	0.10	0.22	4.8
6	Botna (R. Noy)	0.465	2.1	0.45	0.51	8.4
6	Botna (R. Noy)	0.460	2.1	0.44	0.51	8.3
7	Botna (Keushen)	0.130	3.5	0.34	0.11	2.0
8	Botna (Khoresht)	0.037	2.0	0.15	0.12	4.1
9	Kogilnik (Stolnichen)	0.510	2.3	0.40	0.56	9.1
10	Kogilnik (G. Gabena)	1.00	5.2	0.29	0.66	5.6
11	Kogilnik (Bogdanovka)	0.035	6.4	0.06	0.09	1.9
12	Salchea (Luchesht)	0.040	2.2	0.06	0.32	4.7
12	Salchea (Luchesht)	0.040	2.2	0.05	0.38	4.3

[a] Q = water discharge.
[b] B = river width.
[c] h = cross-sectionally averaged depth.
[d] U = flow-averaged velocity.
[e] g = gravitational acceleration and S = channel slope.

considered range and N is the total number of observations]. It shows that the experimental data can roughly be described by the Gaussian curve and, as a first approximation, $U_p = U_c$. However, the tendency of the hydrometric velocity U_c to exceed U_p values is evident (Figure 3). It can be explained by the fact that the hydrometric measurements were performed at local cross sections of the stream, whereas the peak travel velocity integrates the entire river reach. Similar results were previously obtained by Day (1975).

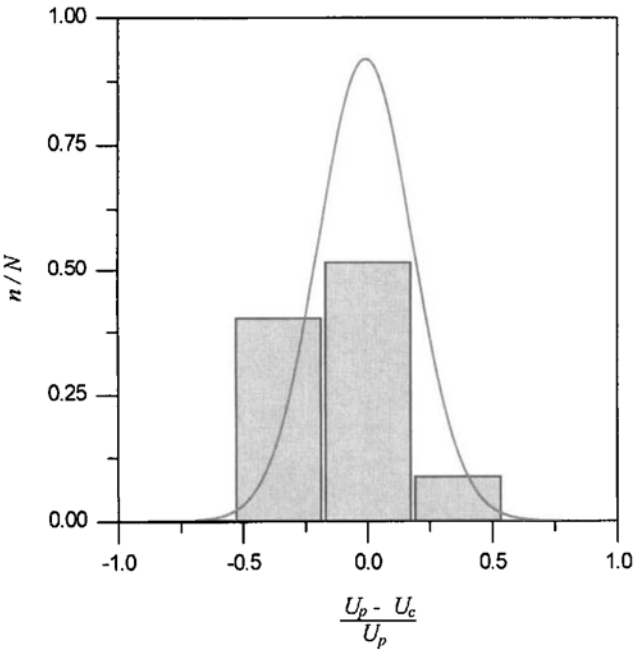

Figure 3—Bar diagram of values $\frac{U_p - U_c}{U_p}$ and its approximation with Gaussian curve.

Decay of Concentration Maximum. From Equation 2, the maximum value of the concentration distribution, $C_{max}(t)$, is

$$C_{max}(t) = \frac{1}{\sqrt{D}} \frac{M}{2A\sqrt{\pi t}} \tag{3}$$

If the experimental results agree with the model (Equation 1), the value of D can be easily estimated on the basis of Equation 3.

To validate Equation 3, we collected data for which C_{max} was proportional to t^{-m}, and for most reaches the value of m proved to be close to 0.5. In three cases an anomalous relationship, in which C_{max} was proportional to $t^{-0.9}$, occurred, and in one case C_{max} was proportional to $t^{-0.2}$. The values of D calculated with the use of the least-squares method for those reaches, where C_{max} is proportional to $t^{-0.5}$, are presented in Table 2. The cases of anomalous behavior are denoted in Table 2 as anomalously high dispersion (AHD) and anomalously low dispersion (ALD). The change of C_{max} in a dimensionless form along the experimental river reaches is shown in Figure 4. This figure reveals that the experimental results at distances greater than 80 to 100 times the river width, B, obey Equation 3. The dimensionless form was obtained from Equation 3 as

$$C_{max} = \frac{M}{2A\sqrt{\pi DB/U}} \frac{1}{\sqrt{x/B}}$$

Hence,

$$\frac{2A\sqrt{\pi DB/U}C_{max}}{M} = \frac{1}{\sqrt{x/B}}$$

Growth of Concentration Distribution Variance. To estimate the spatial variance of concentration distribution, investigation was made of the following hypothesis, which is valid

Table 2—Characteristics of longitudinal dispersion on experimental river reaches.

Reach number	D,[a] m²/s (Eq. 3)	D, m²/s (Eq. 6)	L_m/B	α[2c]	β[c]
1	2.16	AHD	62	—	—
2	AHD	1.30	139	—	—
3	0.19	0.16	29	—	—
4	0.62	0.50	53	0.06	15
5	2.85	3.67	74	—	—
6	0.29	0.27	41	0.06	9
6	0.83	0.96	12	0.07	13
6	0.71	1.06	13	0.08	13
7	ALD	0.31	18	0.03	22
8	AHD	AHD	25	—	—
9	1.1	1.60	16	0.11	11
10	1.91	2.76	89	0.04	22
11	AHD	AHD	217	—	—
12	0.88	0.81	105	0.07	17
12	1.04	1.22	118	0.08	19

[a] D = coefficient of longitudinal dispersion.
[b] L_m/B = mixing length/river width.
[c] α and β = coefficients.

for large x or t and is widely used (Fischer, 1966, and Rutherford, 1994):

$$\sigma_x^2 = U^2\sigma_t^2 \tag{4}$$

Where

σ_x^2 = spatial variance, m²; and
σ_t^2 = time variance, seconds²

The time variance is defined as

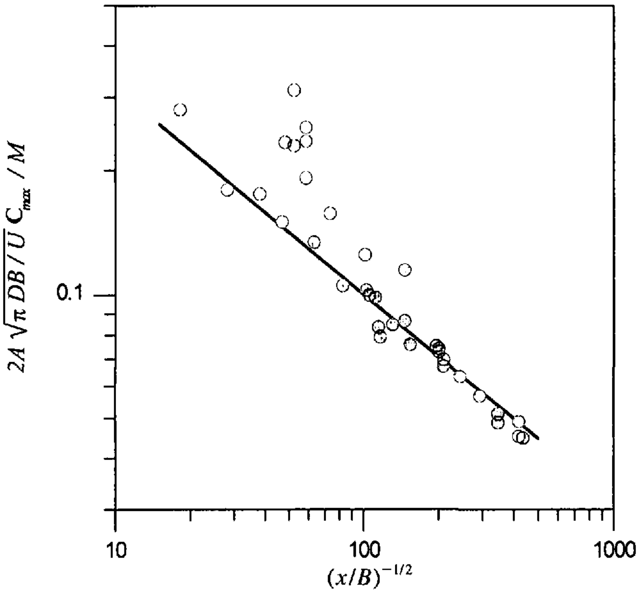

Figure 4—Dimensionless peak concentrations along the experimental river reaches.

$$\sigma_t^2 = \int_0^{+\infty} (t-\mu)^2\bar{C}(t)dt \approx \frac{\sum_{i=1}^{N} C_i t_i^2}{\sum_{i=1}^{N} C_i} - \left(\frac{\sum_{i=1}^{N} C_i t_i}{\sum_{i=1}^{N} C_i}\right)^2 \tag{5}$$

Where

C_i = cross-sectionally averaged concentration at time t, kg/m³ or g/L;
N = number of sampling points; and

$$\mu = \frac{\int_0^{\infty} t\bar{C}(x,t)dt}{\int_0^{\infty} \bar{C}(x,t)dt} \approx \frac{\sum_{i=1}^{N} C_i t_i}{\sum_{i=1}^{N} C_i}$$

Considering the process for sufficiently large t, one can obtain the following (Elder, 1959, and Fischer, 1966):

$$\sigma_x^2 = U^2\sigma_t^2 = 2Dt$$

Or

$$D = \frac{U^2\sigma_t^2}{2t} \tag{6}$$

As validation of Equation 6, analysis of the data $\sigma_t^2 \sim t^k$ showed that in most cases k was close to 1, and thus the change of the variance σ_t^2 appeared to be in good agreement with Equation 6. An AHD with σ_t^2 proportional to $t^{1.7}$ occurred in three cases as in the previous section. The values of D obtained with the use of the least-squares method are presented in Table 2. The downstream change of σ_t^2 in a dimensionless form is shown in Figure 5. This plot shows that experimental results satisfy Equation 6 for the distances x/B greater than 80 to 100. The dimensionless form was deduced from Equation 6 to be

$$D = \frac{U^3\sigma_t^2}{2B}\frac{1}{x/B},\ \frac{U^3\sigma_t^2}{2DB} = x/B$$

The possible explanation of the anomalous dispersion cases can be the following. When considering Equation 1, the existence of the balance between transverse mixing from turbulence and the transverse velocity shear is automatically assumed. According to numerical computations and some field measurements (Rutherford, 1994), this assumption can be accepted only at sufficiently large x or t. However, in some cases (secondary currents, recirculating zones, or very homogeneous or, conversely, very nonuniform transverse velocity distributions), imbalance between velocity shear and transverse turbulent diffusion, even at very large x or t, can still be observed. From this point of view, the case of AHD corresponds to the predominance of velocity shear over transverse turbulent mixing (a case of weak turbulence), whereas in the case of ALD, the turbulent mixing mostly contributes to longitudinal dispersion (a case of weak velocity shear). The ALD behavior occurs in this case because the tracer release was not instantaneous.

The Skewness of Concentration Distributions. An important parameter characterizing the shape of the concentration distribution is the skewness coefficient. The skewness coefficient, Sk, of the concentration time distribution is defined as

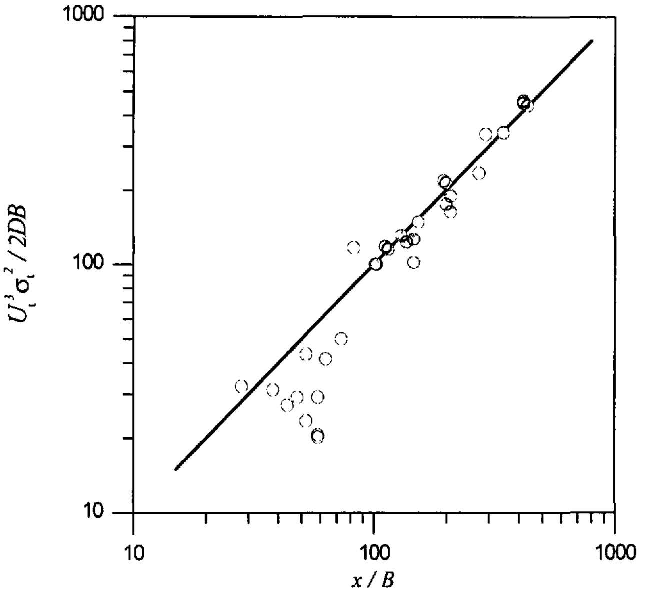

Figure 5—Dimensionless variances along the experimental river reaches.

$$Sk = \frac{1}{\sigma_t^3}\int_0^{\infty} \bar{C}(x,t)(t-\mu)^3 dt \qquad (7)$$

For a dispersion model, Sukhodolov (1993) obtained

$$Sk \sim \left(\frac{Uh}{D}\right)^{-1/2}\left(\frac{x}{B}\right)^{-1/2} \qquad (8)$$

where h is the cross-sectionally averaged depth, m. Nordin and Troutman (1980) also obtained the decrease of Sk proportionally to $x^{-1/2}$.

To check agreement of the experimental results with Equation 8, only the data satisfying Equations 3 and 6 were selected, and only distributions with large numbers of sampling points covering all parts of the cloud were considered. As follows from Figure 6, the skewness of observed concentration distributions does not decrease according to Equation 8. Moreover, in some cases their values increase with the distance from the injection site.

The skewness behavior can be explained within the concept of dead zones (Thackston and Schnelle, 1977, and Valentine and Wood, 1979), but it is not straightforward from the theory developed so far. However, this topic exceeds the scope of this paper and is studied by authors in detail elsewhere (Czernuszenko and Rowiński, 1996).

Properties of Similarity in Concentration Distributions. The results presented in previous sections and the results of other researchers (Day, 1975, and Nordin and Sabol, 1974) indicate that two important features of the longitudinal dispersion model (Equations 3 and 6) roughly correspond to the real process. The main disadvantage is the persistence of skewness in the observed data, which cannot be explained in the context of this model. How the shapes of the experimental distributions of concentration deviate from the modeled one and in which cases the deviations are viewed as insignificant or predictable are important questions.

It is convenient to use dimensionless coordinates for comparison. For a Fickian-type process, the usual way to obtain dimensionless time, τ_σ, is to apply the following expression (Chatwin, 1980):

$$\tau_\sigma = \frac{t-\mu}{\sigma_t} \sim \frac{t-t_p}{\sigma_t} \qquad (9)$$

where t_p is the concentration peak time in seconds.

The concentration can be scaled by the peak value (Day and Wood, 1976). In Figure 7, the dimensionless experimental data and the analytical curve from Equation 2 are presented. To scale experimental distributions, the peak value was calculated from Equation 3 as $M/(\sqrt{2\pi}Q\sigma_t)$. It allows a scatter of the data to be shown with respect to modeled values. Only experimental results that obey Equations 3 and 6 in the range of $x/B > 80$ were plotted. The figure shows rough agreement (with the accuracy of 15 to 20%) with Equation 2 in the upper [$\bar{C}(t) > 0.5\ C_{max}$] parts of the concentration distributions. The leading part of the cloud [$\bar{C}(t) < 0.5\ C_{max}$] is shifted from the Fickian-type distribution. We believe the primary reason for this is that the relationship $\sigma_x^2 = U^2\sigma_t^2$ (which was used for normalization in Figure 7) is only an approximation.

As shown by Beltaos (1980), the value of T_c ($T_c = t_b - t_f$ = duration of concentrations exceeding 50% of C_{max}, and t_b and t_f are the times corresponding to $\bar{C}(t) = 0.5C_{max}$ on the concentration distribution) for Fickian-type distribution is related to σ_t as follows:

$$T_c = 2.24\sigma_t \qquad (10)$$

The validity of this relationship is evident from Figures 7 and

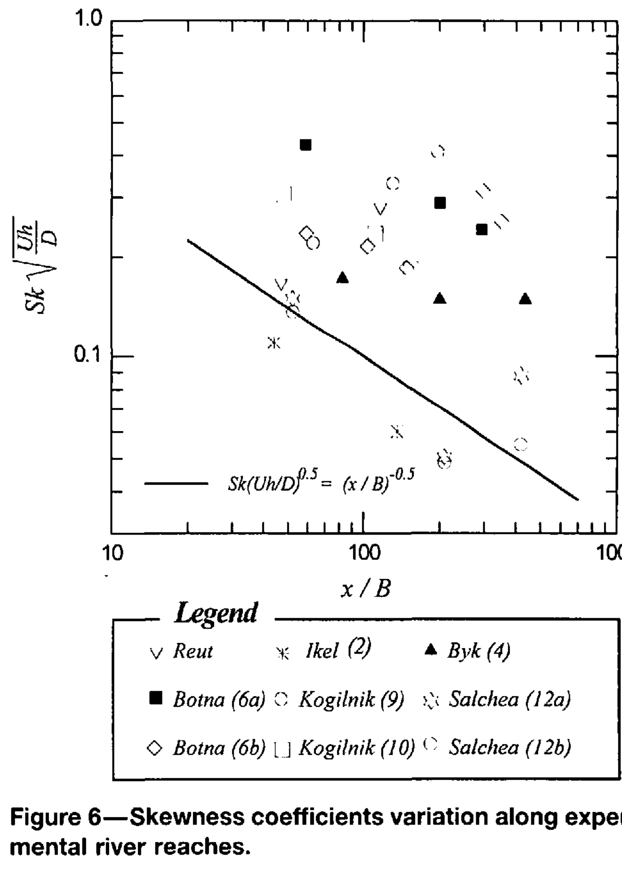

Figure 6—Skewness coefficients variation along experimental river reaches.

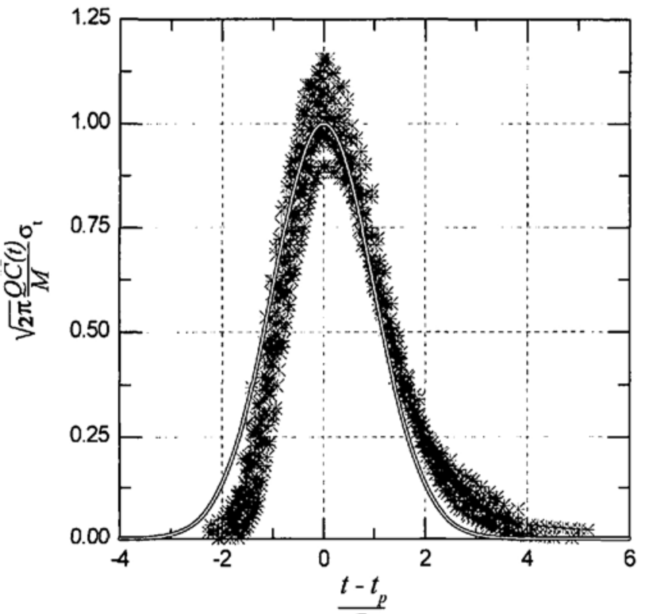

Figure 7—Dimensionless concentration distributions for $x/B > 80$ and Fickian solution.

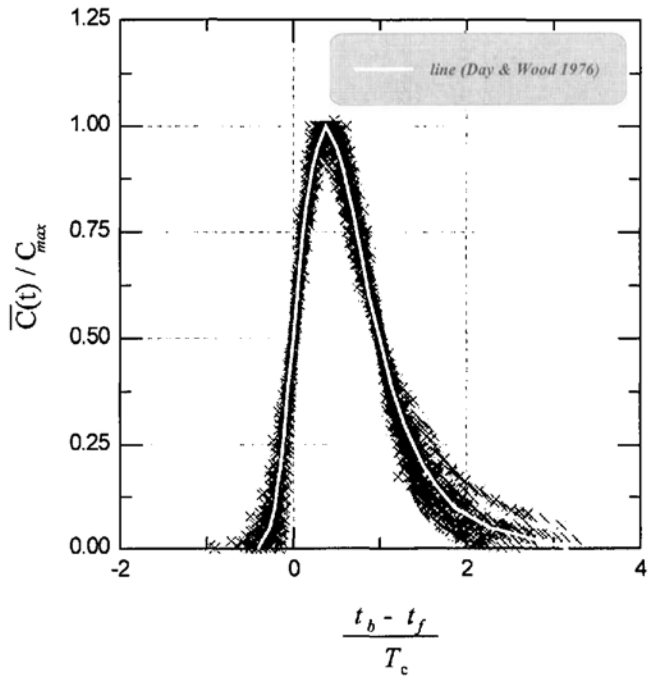

Figure 9—Comparison of experimental results (all distributions) with average distribution proposed by Day and Wood (1976).

8. It provides an additional way to estimate unknown values of σ_t when concentration measurements are limited.

The forms of the dimensionless experimental distributions confirm the idea of similarity (Day and Wood, 1976) to the use of dimensionless average concentration distributions in application calculations. Figure 9 shows the comparison of the average distribution obtained by Day and Wood (1976) for small mountain rivers in New Zealand with the experimental data obtained by the authors of the current study in Moldova. Note that in this case the observed values of $C_{\max}$ were used for scaling.

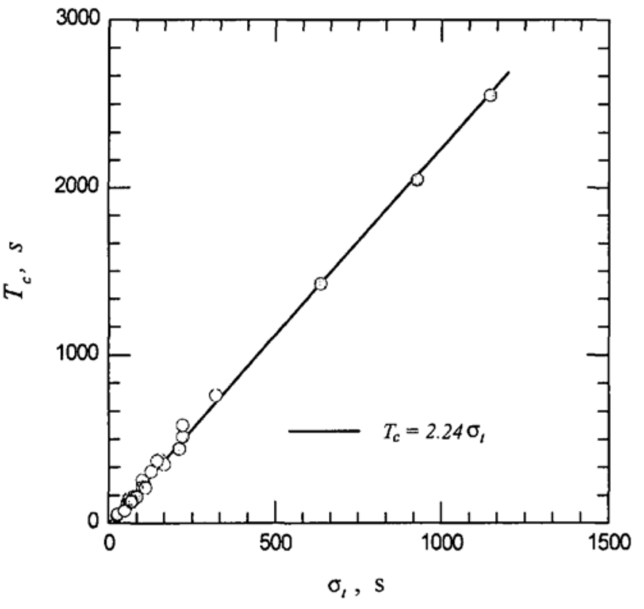

Figure 8—Property $T_c = 2.24\sigma_t$ and comparison with experimental results.

One-Dimensionality and Mixing Length. By definition (Beltaos, 1980), if the concentration dispersion is strictly one-dimensional, with respect to Equation 1,

$$\frac{\partial C}{\partial y} = \frac{\partial C}{\partial z} = 0 \tag{11}$$

Although this condition cannot completely be reached in rivers (Rutherford, 1994), the application of the longitudinal dispersion model always implies it. From a practical point of view, the assumption of one-dimensionality makes sense when the difference of concentration over the cross section is negligibly small.

Another question concerns whether enough time (or distance from the injection site) has elapsed for the dispersion process to obey Fick's law. Following Beltaos (1980), a similarity of concentration distribution exists, and the agreement with the scaling relationships, $C_{\max}$ is proportional to $t^{-0.5}$ and σ_t^2 is proportional to t, can be treated as an indicator for it. When considering the mixing length, the value for the current study was in the range of (80 to 100)B.

The values of the mixing length are typically obtained from an empirical formula (Beltaos, 1980; Beltaos and Day, 1978; and Cunge *et al.*, 1980):

$$L_m = \frac{1.8b^2U}{h\sqrt{ghS}} \tag{12}$$

Where

L_m = mixing length, m;
b = distance between the maximum velocity location and the farthest channel bank, m;
g = gravitational acceleration, m/s^2; and
S = channel slope, m/m.

Calculated values of L_m/B are given in Table 2. These results show that in most cases the value of L_m/B is two to three times less than the measured threshold value of (80 to 100)B, and only in four cases is L_m/B larger than 100.

Parametrization of Longitudinal Dispersion Coefficient. The longitudinal dispersion coefficient can be presented in the following general form (Nikora and Sukhodolov, 1993):

$$D = \frac{1}{2}\frac{\overline{dx'^2}}{dt} = \int_0^\infty \overline{U'(t)U'(t+\tau)}d\tau \tag{13}$$

Where

x' = deviation of a liquid particle from its mean position, m;
U' = deviation of the instant longitudinal velocity of the particle from its average velocity, m/s; and
τ = time shift, seconds.

As a first approximation, the velocity deviation U' can be presented as a sum of two components: a turbulent component, U'_T, and a component stipulated by the transverse heterogeneity of the mean local velocity, U'_W. Substituting U'_T and U'_W into Equation 13, performing simple transformations, and neglecting correlation between the components U'_T and U'_W gives $D = \sigma_t^2\ T_T + \sigma_W^2 T_W = D_T + D_W$, where σ_T^2, σ_W^2 and T_T, T_W are variances and time Lagrangian scales of the components U'_t and U'_W, respectively, and D_t and D_W are the turbulent and velocity shear components of the total dispersion coefficient.

It has been shown that the contribution of longitudinal turbulent diffusion in the dispersion process in rivers is negligibly small in comparison with the velocity shear effect (Elder, 1959, and Rutherford, 1994); therefore,

$$D \approx D_W = \sigma_W^2 T_W \tag{14}$$

From physical considerations, and based on the dimensional analysis, the following can be assumed (Sukhodolov *et al.*, 1995):

$$\overline{\sigma_W^2} = \alpha^2 U^2 \tag{15}$$

$$T_W = \beta\frac{B}{U} \tag{16}$$

where α and β are coefficients. Hence, Equation 14 can be rewritten as

$$D = \alpha^2 \beta UB \tag{17}$$

It is easy to see that the coefficient α characterizes the degree of heterogeneity of the velocity distribution. The empirical analogy of Equation 17 was obtained by Rochusaar and Paal (1970) for small Estonian rivers in the form $D = 1.5UB$. The experimental results for Moldovian rivers obey the following relationship obtained by using the least-squares method:

$$D = 0.83UB \tag{18}$$

An earlier reported value of 1.1 for the coefficient in Equation 18 was preliminary (Nikora and Sukhodolov, 1993). The comparison of these data with other investigations is presented in Figure 10. It is worth pointing out here that other, earlier developed expressions for D do not agree with data in the current study as well as Equation 18. The data in Figure 10 support the idea that the value $\alpha^2\beta$ cannot be treated as universal for rivers.

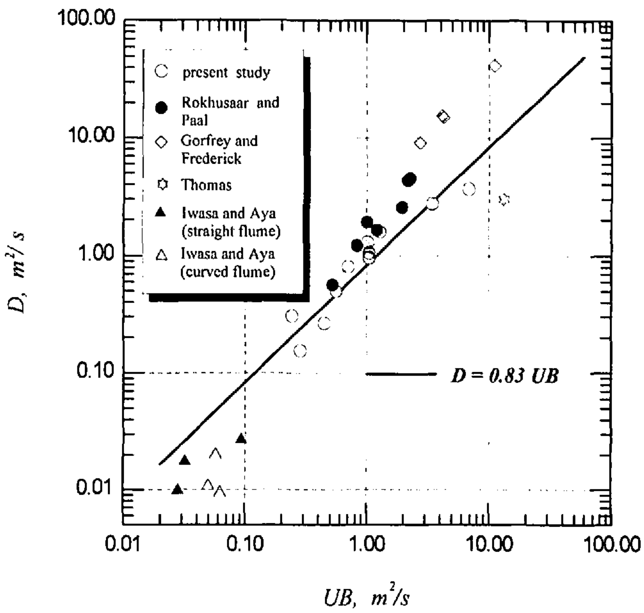

Figure 10—Dispersion coefficients *D* (from Equation 6)—present study and literature examples.

It was proposed (Sukhodolov *et al.*, 1995) that the parameter α^2 can be expressed as follows

$$\alpha^2 = \frac{1}{N}\sum_{i=1}^{N}\left[\frac{1}{AU_{ai}^2}\sum_{j=1}^{k}(U_j = U_{Ai})^2 a_j\right] \tag{19}$$

Where

U_j = local mean velocity, m/s;
U_{Ai} = cross-sectionally averaged velocity, m/s;
a_j = unit area of cross section, m^2;
k = number of measurement points at a cross section; and
N = number of measurement cross sections in the river reach.

Note that the detailed velocity measurements are required to get a reliable value of α^2. After α^2 is determined, the coefficient β can be estimated directly from Equation 17. When available, the obtained values of α and β are presented in Table 2. To be more precise, the values shown were determined in cases when the number of velocity measurements justified a suitable averaging procedure.

The values of α and β ranged from 0.17 to 0.33 and from 9 to 22, respectively. All river reaches, used to estimate α and β, are characterized by artificially straightened channels with alternate bars. The longitudinal sizes of those alternate bars are as large as five to six channel widths (Nikora, 1992). If the alternate bars are considered major channel forms, the spatial Lagrangian scale $L_W = LUT_W$ depends on alternate bar length L_b. Thus,

$$L_W \approx UT_W \approx (9 - 22)B \approx (1.6 - 4)L_b \tag{20}$$

Summary and Conclusions

The scaling relationship $C_{max} \sim t^{-0.5}$ derived from the one-dimensional dispersion model roughly agreed with experimental data obtained for x/B greater than 80 to 100, except in four cases, when an anomalous behavior was observed. The experimental data also approximately satisfy the relationship $\sigma_t^2 \sim t$ for x/B greater than 80 to 100, except in three cases of anomalous dispersion. The possible explanation of AHD can be the following:

- The process takes place in its early stage, and the condition that t be much greater than T_W is not satisfied;
- For cases when t is much greater than T_W, AHD takes place because of the presence of an extremely high level of nonuniformity of velocity distribution at cross sections along the river reach and the influence of large zones at the lee sides of alternate bars.

The case of ALD can be explained by the low degree of the flow heterogeneity and by imperfection of the tracer release technique. The skewness of concentration distributions does not decrease with the growth of the distance according to $x^{-1/2}$, and its behavior is different for every investigated river reach. The upper parts of experimental distributions $[\bar{C}(t) > 0.5C_{max}]$ are in better agreement with the Fickian solution than are their lower parts. The process approaches Fickian behavior at distances two to three times larger than could be estimated with the widely used empirical Equation 12. The Lagrangian spatial scales of longitudinal dispersion were estimated to be as large as two to four lengths of alternate bars.

Finally, the present study highlights the need both for caution when the dispersion model is used and for further field investigations. The main objective of future investigations should perhaps be directed to explaining the asymmetry of the concentration distributions. It cannot be interpreted according to the Fick theory, and new ideas are needed. A possible interpretation is through the application of the well-known dead-zone model. However, new evaluations of the statistical parameters for this model and experimental determination of the model parameters are needed. The presented results are a good basis for this purpose. Such studies have already been carried out by authors, and results are expected to be reported soon.

Acknowledgments

Credits. This research was supported by the Institute of Geophysics and Geology in the Republic of Moldova, the Institute of Geophysics in Poland, and National Institute of Water and Atmospheric Research in New Zealand. Financial support for Dr. Sukhodolov was provided by the scholarship program of the Institute of Geophysics, Polish Academy of Sciences. Hydrologists Anatol Naumenko and Nicholas Arnaut assisted with field work.

Authors. Alexander N. Sukhodolov is a visiting postdoctoral fellow, Paweł M. Rowiński is a research associate, and Włodzimerz Czernuszenko is a professor at the Institute of Geophysics, Polish Academy of Sciences, Warsaw. Vladimir I. Nikora is a scientist at the National Institute of Water and Atmospheric Research, Christchurch, New Zealand. Correspondence should be addressed to P. Rowiński at the Institute of Geophysics, Polish Academy of Sciences, ul. Ks. Janusza 64, 01-452 Warsaw, Poland.

Submitted for publication February 2, 1996; revised manuscript submitted August 21, 1996; accepted for publication September 19, 1996.

References

Beltaos, S. (1980) Longitudinal Dispersion in Rivers. *J. Hydraul.*, **106**, HY1, 151.

Beltaos, S., and Day, T.J. (1978) A Field Study of Longitudinal Dispersion. *Can. J. Civ. Eng.*, **5**, 572.

Chatwin, P. (1980) Presentation of Longitudinal Dispersion Data. *J. Hydraul.*, **106**, HY1, 71.

Czernuszenko, W. (1990) Dispersion of Pollutants in Flowing Surface Waters. In *Encyclopedia of Fluid Mechanics*. Gulf Publishing Company, Houston, Tex., 119.

Czernuszenko, W., and Rowiński, P.M. (1997) Properties of the Dead-Zone Model of Longitudinal Dispersion in Rivers. *J. Hydraul. Res.*, **35**, 4, 491.

Cunge, J.A.; Holly, F.M.; and Verwey, A. (1980) *Practical Aspects of Computational River Hydraulics*. Pitman Advanced Publishing Program, London, U.K.

Day, T. (1975) Longitudinal Dispersion in Natural Channels. *Water Resour. Res.*, **11**, 6, 909.

Day, T., and Wood, I. (1976) Similarity of the Mean Motion of Fluid Particles Dispersing in a Natural Channel. *Water Resour. Res.*, **12**, 4, 655.

Elder, J. (1959) The Dispersion of Marked Fluid in Turbulent Shear Flow. *J. Fluid Mech.*, **5**, 544.

Fischer, H. (1966) A Note on the One-Dimensional Dispersion Model. *Air Water Pollut. Int. J.*, **10**, 443.

Nikora, V. (1992) *Channel Processes and Hydraulics of Small Rivers* [Russian]. Kishinev, Shtiinca.

Nikora, V., and Sukhodolov, A. (1993) Longitudinal Dispersion of Conservative Pollutants in Small Rivers. *Proc. Adv. Hydro-Sci. Eng.*, Washington, D.C., **1**, 2, 379.

Nordin, C., and Sabol, G. (1974) Empirical Data on Longitudinal Dispersion in Rivers. Water Resources Investigations 20–74, U.S. Geol. Surv., Washington, D.C.

Nordin, C., and Troutman, B. (1980) Longitudinal Dispersion in Rivers: The Persistence of Skewness in Observed Data. *Water Resour. Res.*, **16**, 1, 123.

Rochusaar, L., and Paal, L. (1970) The Results of the Experimental Investigation of the Longitudinal Dispersion Coefficient in Open Channels [Russian]. *Proc. Tallin Politech. Inst., A*, 298, 6.

Rutherford, J.C. (1994) *River Mixing*. John Wiley and Sons, New York, N.Y.

Sayre, W.W. (1975) Dispersion of Mass in Open-Channel Flow. Hydrology Paper N 75, Colo. State Univ., Fort Collins.

Sukhodolov, A. (1993) Longitudinal Dispersion and Its Quantitative Estimation in Small Rivers [Russian]. Ph.D. thes., Odessa, Ukr.

Sukhodolov, A.; Rowiński, P.M.; and Nikora, V. (1995) Estimate of Advection Impact on Longitudinal Dispersion in Rivers [Pol.]. *Proc. XV Pol. Summer Hydraul. School*, Wrocław—Trzebieszowice, Pol., 213.

Taylor, J. (1954) The Dispersion of Matter in Turbulent Flow Through a Pipe. *Proc. Royal Society, Ser. A.*, 223.

Thackston, E., and Schnelle, K. (1977) Predicting Effects of Dead Zone on Stream Mixing. *J. Sanit. Eng.*, **96**, SA2, 975.

Valentine, E., and Wood, I. (1979) Longitudinal Dispersion with Dead Zones. *J. Hydraul.*, HY8, 975.

Vuksanovic, V.; De Smedt, F.; and Van Meerbeeck, S. (1996) Transport of Polychlorinated Biphenyls (PCB) in the Scheldt Estuary Simulated with the Water Quality Model WASP. *J. Hydrol.*, **174**, 1.

West, J.R., and Mangat, J.S. (1986) The Determination and Prediction of Longitudinal Dispersion Coefficients in a Narrow, Shallow Estuary. *Estuarine Coastal Shelf Sci.*, **22**, 161.