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Sediment Transport in a River under One-Dimensional and Unsteady Flow Conditions

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Abstract

An attempt to describe the one-dimensional sediment transport in a river under unsteady flow conditions is presented. A thesis was formulated that the influence of turbulent dispersion of sediment in the main direction of the river flow is of significant importance in prognosing the transport of suspended matter in practical aspects, especially as regards protection of water intakes and efficient operation of water treatment plants. The transport of suspended matter is described here by parabolic differential equation. A mathematical model has been developed and applied to forecasting sediment concentration changes during freshets in the outlet cross section of the Vistula River to Goczałkowice Reservoir. The results of field studies and numerical simulations by use of the developed model revealed that the model accuracy is satisfactory for its practical applications in water intake protection against the freshet effects. Simultaneously the assumed thesis was confirmed that the sediment transport in the river under unsteady flow is of a dispersive nature.

1. Introduction

The formulation of movement and transportation of solid granular particles in rivers belong to the basic phenomena considered in practice in water engineering. The quantitative determination of those phenomena is often necessary in the case of designing, constructing and operating hydrotechnical objects, especially water intake points and water treatment stations. Such recognition requires the preparation of short-term prognoses of sediment concentration changes in water taken in from the river and supplied to a water treatment station.

A practical need for such forecasting is particularly important in the case of water intake in the cross section of Strumień on the Vistula River. Considerable sediment loads appearing in the Vistula River during freshets create risks for the proper functioning of this water intake. Sediment transport under steady or nearly-steady flows has extensive theoretical interpretation and rich experimental documentation. Mathematical methods for simulating this type of sediment transport find practical application in hydroengineering and protection of water resources.

The problem of sediment transport under unsteady flow conditions has been described theoretically in the form of general mass balance equations, however the results of the experiments, especially when referred to natural conditions, are so far insufficient to formulate practical methods for the needs of hydroengineering.

An attempt was undertaken to elaborate a mathematical model of suspended sediment transport and to perform a full cycle of field experiments on a real object. The proposed mathematical model of sediment transport may be applied to prognosing the sediment loads during the propagation of freshet wave. On the basis of this prognosis the water user will be able to determine rational modification of the water treatment process.

It was assumed that one of the significant factors of sediment transport in the conditions of freshet wave propagation is the process of turbulent dispersion of suspended matter along the main direction of flow. The present formulas describing sediment transport concern mostly uniform flow and do not consider the longitudinal dispersion of suspended matter. The previously formulated equations concerning sediment transport under non-uniform flow conditions have not been tested at all or only in laboratory conditions. Thus the concept of the model is based on a thesis that the impact of turbulent dispersion of sediments in the main direction of the river flow is of significant importance for prognosing sediment transport in practical aspects like protection of water intakes and effective operation of water treatment stations.

The section of the Vistula River above the Goczałkowice Reservoir was chosen to gather the field input data and apply the developed model for suspended sediment transport simulation and forecasting.

2. A Brief Review of Literature on Sediment Transport

The first work on the river sediment movement was of a descriptive character, without any theoretical generalizations. From the beginning of 19th century rapid development in theoretical interpretation of river sediment has been observed. The research on this problem was carried out in two directions, i.e. vertical and longitudinal suspended matter dispersion. In both cases the theoretical interpretation took into consideration the phenomenon of turbulent diffusion of mass in stream.

A significant contribution to the development of the investigations on the vertical dispersion of suspended matter were the works of such scientists as Hurst (Hurst 1929), Rouse (Rouse 1937), Kalinske (Kalinske 1940), Einstein (Einstein et al. 1955) et al. On the basis of the theoretical research results practical formulas for the determination of the amount of transported suspended matter were elaborated. The best known are Einstein's (Einstein 1950), Bishop's (Bishop et al. 1965), Laursen's (Laursen 1958), Graf's (Graf 1971), Zamarin's (Zamarin 1948) and Gonczarow's (Krenkel et al. 1980) formulas. In Poland the pioneers of research on the vertical dispersion of suspended matter were Dębski (Dębski 1939, 1946, 1957) and Jarocki (Jarocki 1957). The works of those scientists established the background. Further progress in investigations was made thanks to the research carried out by such scientists as Skibiński (Skibiński et al. 1981, 1982), Dąbkowski (Dąbkowski et al. 1982), Gładki (Gładki, Myczka 1968), Brański (Brański Kondzielski 1985), Pasławski (Pasławski 1971), Ciepielowski (Ciepielowski et al. 1968) and others.

The research performed on sediment transport in open beds shows that the process of longitudinal dispersion of suspended matter under unsteady flow conditions is insufficiently recognized to be applied in practical solutions. The previous equations of suspended matter transport in such flow conditions, considering the longitudinal diffusion of suspended matter, have not been verified in true conditions, at the best their reliability was tested only in laboratory experiments.

It was for cognitive reasons as well as practical necessity of water intake protection and the improvement of operation of water treatment stations that justify the need to undertake research which would develop a mathematical method for the determination of suspended matter transport in unsteady flow verified through field investigation.

3. Simplifying Assumptions

The formulation of an equation of sediment transport under unsteady flow conditions demands certain assumptions simplifying the actual process of this complex phenomenon:

(a) Uniform concentration distribution of particles in all points of the stream cross section, perpendicular to the main direction of movement (x) is assumed.

(b) The mass balance of individual sediment fractions does not change during their transport. In other words, the collisions of sediment particles during transport do not cause any changes in the granulometric composition.

(c) The sediment is monodisperse, i.e. it consists of uniform particle sizes. Thus only the transport of the main fraction of sediments from 1.0 mm to 0.1 mm that covers approx. 80% of the sediment mass is concerned, assuming that the influence of the remaining fractions on the operation of water treatment stations may be neglected.

(d) The presence of sediments does not affect the flow pattern. The exchange of energy and momentum between water and sediment is neglected. The application of such an assumption is possible due to the fact that in the proposed sediment transport model it is assumed to apply the flood routing procedure, verified in the presence of sediment in flowing water.

According to the afore-mentioned assumptions, the applicability of the proposed method for predicting sediment transport is limited only to narrow and shallow rivers, for which the influence of vertical and lateral mass dispersion on the spatial distribution of sediment concentrations can be neglected. The sector of the Vistula River under investigation is classified as this type of river.

4. Model of Sediment Transport

The basic equation describing the dispersion of pollutants is the equation of turbulent dispersion. It is derived from the mass conservation law. The distribution of pollution is defined against the (x, y, z) reference system using the velocity field $u(x, y, z, t)$ and scalar field of sediment concentrations $C(x, y, z, t)$, that do not influence the water density. The half empirical equation of turbulent diffusion is as follows:

$$\begin{aligned}\frac{\partial(C)}{\partial t}+\frac{\partial(u_xC)}{\partial x}+\frac{\partial(u_yC)}{\partial y}+\frac{\partial(u_zC)}{\partial z}&=\\=\frac{\partial}{\partial x}\left(D_x\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_y\frac{\partial C}{\partial y}\right)&+\frac{\partial}{\partial z}\left(D_z\frac{\partial C}{\partial z}\right)\end{aligned} \tag{1}$$

where D_{xyz} is the diffusion coefficient in directions x, y, z.

Equation (1) may be reduced to a one-dimensional longitudinal form by taking average values of all parameters across the section of the stream and considering concentration only as a function of x and t, as given below:

$$U=\frac{1}{A}\int_A^0 \bar{u}dA, \tag{2}$$

$$C=\frac{1}{A}\int_A^0 \bar{c}dA \tag{3}$$

where A is the cross-sectional area and $\bar{u}$ and c are time averaged components of velocity and concentration. Equation (1) reduces to:

$$\frac{\partial(AC)}{\partial t}=-\frac{\partial(UAC)}{\partial x}+\frac{\partial}{\partial x}\left(AE\frac{\partial c}{\partial x}\right) \tag{4}$$

where E is an effective longitudinal dispersion coefficient.

Equation (4), derived on the basis of theoretical considerations, describes the mass distribution in the prismatic channel of a constant cross section. In natural conditions, especially in the case of the bed of the Vistula River section, local irregularities of bed geometry that cause local increases and decreases of flow velocity in relation to the mean water velocity appear. In order to address that fact along with the possibility of local unidentified inflows of sediments along the course of the river, it is necessary to introduce into equation (4) the function $f(C)$ considering the relevant fluctuations of sediment concentrations resulting from the above described phenomena in a simplified manner. The simplification consists of assuming constant processing of those phenomena along the entire path of sediment transport. In the physical sense the function $f(C)$ is understood as the so called "source function" with the form:

$$f(C) = \pm KAC \tag{5}$$

where:

K – coefficient of sediment mass sources and sinks along the river course [s^{-1}]. Considering the relation (5), equation (4) finally receives the following form:

$$\frac{\partial(AC)}{\partial t} = -\frac{\partial(u_x AC)}{\partial x} + \frac{\partial}{\partial x}\left(AE\frac{\partial C}{\partial x}\right) \pm KAC. \tag{6}$$

This may be interpreted as an unsteady one-dimensional convective-diffusion equation with cross-sectional area, velocity and dispersion coefficient varying with distance downstream.

The partial differential equation of the form (6) was solved by numerical method. A finite-difference method with the explicit scheme was applied.

The calculations were carried out under the following conditions:

(a) boundary conditions:

$$for \quad x = 0 \quad C(x_0 t) = C_0(t), \tag{7}$$

$$x = k \quad C(x_k t) = C_k, \tag{7a}$$

$C_0(t)$ – concentrations of suspended solids observed in the initial cross-section;

(b) initial condition:

$$for \quad t = 0 \quad C(x t_0) = C_p, \tag{8}$$

C_p – mean concentration of suspended solids observed in the river stretch studied before water freshet.

For the above presented model a computer program in FORTRAN 77 was developed. The basic parameters of the proposed model for sediment transport are:

K – coefficient of losses or sources of suspended matter – also called the decay coefficient – along the path of its transport [s^{-1}];

E – coefficient of longitudinal dispersion of suspended matter [$\mathrm{m}^2 \cdot \mathrm{s}^{-1}$].

Coefficient K represents total effect of sources or losses of suspended sediments to the flowing stream in a selected river section. It is assumed that the value of K remains unchanged during freshet and in the whole length of the river section investigated. According to the accepted interpretation, the formula of the equation describing the sources or losses of suspended mass of sediment in the way of its transport is as follows:

$$\frac{dC}{dt} = K \cdot C. \tag{9}$$

Integrating in the range of C_0 and time t_0 to C_k and time t_k we obtain:

$$\ln C_k = \ln C_0 - K(t_k - t_0), \tag{10}$$

$$C_k = C_0 \cdot e^{-K(t_k - t_0)}, \tag{11}$$

$$K = \frac{2.303}{(t_k - t_0)} \lg \frac{C_0}{C_k}. \tag{12}$$

Due to the necessity of considering the dispersion process, it seems better to apply the dependence of the K value to the total mass of suspended matter entering the investigated river section – M_0 and leaving it – M_k:

$$K = \frac{2.303}{(t_k - t_0)} \lg \frac{M_0}{M_k}. \tag{13}$$

The starting point for the determination of longitudinal dispersion coefficient of suspended matter is the Reynold's hypothesis, according to which the process of suspended matter dispersion is the same as the process of pollutants dissolved in water. In this case the problem of the E coefficient estimation consisted in such selection of the empirical formula connecting the E values with the hydraulic parameters of flow that would recflect the character of the investigated river section at best.

Boczar (Boczar 1980) provided an exhausting review of methods for estimation of longitudinal dispersion coefficient in rivers. On the basis of the analysis of applicability of individual formulas and the hydraulic properties of the investigated river section carried out by Boczar, the Rohussar and Paal formula has been selected (Rohussar and Paal 1969):

$$\frac{E}{R_h \cdot u_*} = 16 \left(\frac{U}{u_*}\right)^{1.25} \tag{14}$$

where:

E – longitudinal dispersion coefficient [$\mathrm{m}^2 \cdot \mathrm{s}^{-1}$],

R_h – hydraulic radius [m],

u_* – dynamic velocity $[\mathrm{m \cdot s^{-1}}]$,
U – mean flow velocity in the longitudinal direction $[\mathrm{m \cdot s^{-1}}]$.

The R_h values, like the E and U values, are variable in time. It is a formula considering the dependence of the dispersion coefficient E on the hydraulic resistance of the bed. This formula was obtained on the basis of field studies on natural beds.

Using equation (14) and the relevant hydraulic parameters determined in the process of wave propagation, it is possible to determine the E values in the function of time and distance.

Numerical experiments were carried out, that consisted in determining the changes of suspended matter concentration for selected freshet by the following adequately modified model parameters:

- coefficient of suspended matter sources and sinks – K,
- longitudinal dispersion coefficient – E,
- mean flow velocity in the longitudinal direction – U.

As a result of the performed analysis it was stated that the model is less sensitive to the variability of the K coefficient; whereas in the case of variability of longitudinal dispersion coefficient E values and variability of flow velocity U, the model shows considerable sensitivity. This sensitivity indicates the necessity to carry out a careful estimation of the values of both these model parameters.

5. Description of the Field Study Area

The model developed has been applied to simulate sediment concentration variations during freshets on the Vistula River in the reach between the cross sections: Skoczów-Bielsko road bridge (km 71.080) in Skoczów and Skoczów-Chybie road bridge (km 62.00) in Drogomyśl, i.e. the outlet section of the river into the Goczałkowice Reservoir.

The choice of the field study area was influenced by practical factors. For several years the Upper Silesian Water Supply Plant – the main user of the Vistula outlet stretch and the Goczałkowice Reservoir – points to the problem of proper functioning of water intake points in the case of rapid increases of suspended matter concentration in water during freshets in the Vistula River. Rapid increases of suspended solids result in serious disturbances in technological process of water treatment and operation of technical units like increased failure frequency of pumps, silting of settlement tanks and pipes. The removal of the excessive water turbidity is usually work consuming and expensive. This problem may be solved by a suitable system of warning early enough for the servicing personnel of water intakes to undertake necessary activities towards the elimination or minimization of the water freshet results in the Vistula River. Functioning of such a warning system demands the application of a prognostic tool with the help of which it will be possible to determine the concentration value and load of suspended solids that will be transported in the water intake cross section during the passing of the freshet wave. The developed mathematical model of sediment transport can function as such a prognostic tool.

The Vistula River in the selected section flows in a uniform bed, corrected by sills, the designed height of which was lowered to a considerable degree as a result of silting. The Vistula River bed is embanked from both sides and do not receive any natural tributaries or artificial water discharges and waste-water.

The choice of the cross section Skoczów as the initial section of the river stretch investigated was dominated by the fact that a limigraphical station of the Institute of Meteorology and Water Management carrying out continuous observation of water levels operates in this stretch. Thanks to that it is possible to monitor the tendencies of water level increase characteristic of freshets.

The cross section Drogomyśl, closing the investigated section of the Vistula River, is located 9.08 km from the initial cross section – Skoczów. Access to the historical observation records (since 1963 – water gauge of the Institute of Meteorology and Water Management) and the fact that the Drogomyśl cross section is located a short distance from the Vistula outlet to the Goczałkowice Reservoir i.e. approx. 2300 m, decided on the choice of that point as the closing cross section.

6. Method of Field and Laboratory Measurements

In both monitoring sites i.e. cross sections of Skoczów and Drogomyśl, water sampling and observations of water-gauges during freshets were carried out.

The measurements and observations comprised four freshets taking place in the following periods:

FRESHET No. 1. from 3.00 p.m., 02. 06. 85 to 9.00 p.m., 03. 06. 85
FRESHET No. 2. from 9.00 p.m., 29. 12. 86 to 4.00 p.m., 31. 12. 86
FRESHET No. 3. from 10.00 p.m., 21. 05. 87 to 8.00 p.m., 23. 05. 87
FRESHET No. 4. from 6.00 a.m., 05. 06. 87 to 8.00 p.m., 06. 06. 87

In both cross sections the samples were collected from the middle of the main stream, from a depth of approx. 0.5 m from the water level using metal containers. The collected water samples were submitted to the laboratory after one or two days. In these samples the contents of total suspended solids and mineral (solid) and organic (volatile) fractions were determined using the weight method. In addition, some of the suspended matter samples were subjected to granulometric analysis. The results of the granulometric analysis show that in water samples collected during all recorded freshets recorded, the granulometric composition of the suspended matter was similar. It contained the biggest amount – from 76–79 per cent – of weight fraction with a diameter of 0.1–1.00 mm; 10 per cent with a diameter of 0.05–0.1 mm and 10–11 per cent with a diameter of 0.02–0.05 mm.

As the major one, the fraction 0.1–1.0 mm, was assumed to be representative for the whole mass of suspended matter.

7. Experimental Estimation of Model Parameters

According to the accepted model parameters estimation method and on the basis of the results from field and laboratory measurements the values of the suspended solids sources and/or sinks coefficients, as well as coefficients of suspended solids dispersion for the observed water freshets were determined.

Following the assumed method the coefficient of suspended solids sources and sinks – K is determined on the basis of equation (13):

$$K = \frac{2.303}{(t_k - t_0)} \lg \frac{M_0}{M_k} \tag{15}$$

where:

t_0 – time of commencement of freshet,
t_k – time of freshet ending,
M_0 – total mass of suspended solids transported to the initial cross section of Skoczów,
M_k – total mass of suspended solids transported to the final cross section of Drogomyśl.

For the water freshets observed the values of K coefficient were obtained in the following range: $3 \cdot 10^{-7}\ \mathrm{s}^{-1} - 1.3 \cdot 10^{-7}\ \mathrm{s}^{-1}$. These values are close to zero which means that the selected object of field studies satisfactorily fulfills the assumption of the transport of the whole mass of suspended solids introduced into the section.

The method for the determination of the coefficients of longitudinal dispersion of suspended matter is based on the Reynold's hypothesis which assumes that there exists proportionality between the suspended matter dispersion coefficient and the coefficient of substances forming a homogeneous mixture with water, which can be expressed by the following expression:

$$D_{x(z)} = \beta \cdot D_{x(w)} \tag{16}$$

where:

$D_{x(z)}$ – longitudinal diffusion coefficient of suspended solids,
$D_{x(w)}$ – longitudinal diffusion coefficient of dissolved substances,
β – proportionality factor.

According to Coleman (Coleman 1980), the proporrtionality factor β is determined from the following formula:

$$\beta = 1 + 2\left(\frac{v_s}{v_*}\right) \tag{17}$$

where:

v_s – hydraulic characteristics of the main sediment fraction [$\mathrm{m \cdot s^{-1}}$],
v_* – dynamic flow velocity [$\mathrm{m \cdot s^{-1}}$].

Using the above presented relationship as well as the mean values of v_s and u_* obtained from measurements and calculations, the β values were calculated in the range close to unity. So the assumption of analogy between the dispersion of suspended solids and substances soluble in water finds full justification.

Following that way of reasoning, the values of E coefficients were determined using Rohussar and Paal's equation. The following values of E coefficient were obtained for the freshets observed (Table 1).

The calculated E values correspond to the values obtained by Boczar and other authors. Such estimated E values were used for the simulation of sediment transport under the unsteady-state flow conditions in the river.

8. Calculation Results and Model Verification

In order to apply the proposed model practically a computing program in FORTRAN 77 was developed. This program allowed for the determination of time and longitudinal changes of suspended solids concentrations in the Vistula River on the path of their transport between the cross sections Skoczów and Drogomyśl. The calculation results are presented in Figs. 1–4.

The presented diagrams of the changes of suspended matter concentration illustrate the shift in time of the maxims of suspended matter concentrations diagrams in Skoczów and Drogomyśl. This shift, resulting from the mean time of freshet wave flow along the investigated sector was 90 min for the observed water freshets.

The calculation results reflect the flattening of suspended matter concentration curves in time relation, calculated for the cross section Drogomyśl in relation to that determined in the beginning of the sector i.e. in the cross section Skoczów. The flattening of the concentrations graph is formed on the path of suspended matter transport and is the proof of the longitudinal dispersion activity. The proposed model of suspended matter transport simulates this process in correspondence with the measured values.

The following three estimation criteria were applied in order to assess the accuracy of the simulation of distribution of actual concentrations by the application of mathematical model:

Table 1. Selected values of longitudinal dispersion coefficient of suspended solids [$m^2 \cdot s^{-1}$]

Date-hour		Skoczów	Intermediate cross sections				Drogomyśl
		Km 71.0	Km 69.0	Km 67.0	Km 65.0	Km 62.0	Km 62.0
2.06.85	8.00 a.m.	10.68	21.80	21.46	21.17	21.51	18.26
	10.00 a.m.	10.93	22.23	21.97	21.73	22.11	18.78
	5.00 p.m.	12.95	25.17	24.74	25.46	23.30	21.05
	8.00 p.m.	14.53	27.27	26.55	27.19	24.81	22.36
	11.00 p.m.	21.05	35.49	33.90	34.15	30.63	27.15
3.06.85	1.00 a.m.	27.52	43.15	41.46	41.93	37.67	33.39
	3.00 a.m.	37.70	53.95	51.76	52.32	46.93	41.53
	5.00 a.m.	39.48	56.25	55.29	56.96	51.92	46.63
29.12.86	10.00 p.m.	5.55	13.39	13.24	13.07	12.60	11.46
30.12.86	1.00 a.m.	11.76	22.47	20.04	19.30	16.78	14.48
	4.00 a.m.	20.08	35.01	32.85	32.55	28.71	24.99
	7.00 a.m.	27.06	42.86	41.68	42.49	38.41	34.23
	3.00 p.m.	16.90	30.72	30.63	32.07	29.86	27.44
	9.00 p.m.	14.42	27.53	27.49	28.59	26.39	24.02
31.12.86	1.00 a.m.	12.28	24.66	24.95	26.15	24.29	22.24
	1.00 p.m.	23.08	38.26	37.32	38.12	34.51	30.77
21.05.87	11.00 a.m.	34.47	51.16	50.54	52.34	48.01	43.45
22.05.87	3.00 a.m.	47.22	63.53	61.73	63.10	57.14	51.04
	7.00 a.m.	67.76	81.93	79.98	82.11	74.46	67.21
	10.00 a.m.	90.37	99.51	95.67	97.32	88.16	80.21
	2.00 p.m.	78.91	92.29	93.39	98.36	92.04	86.27
	5.00 p.m.	31.48	49.88	54.02	59.51	57.37	54.24
	9.00 p.m.	25.18	41.08	41.02	42.82	39.65	36.23
23.05.87	5.00 a.m.	59.14	73.74	69.90	70.06	62.29	54.73
	9.00 a.m.	61.88	77.12	75.86	78.37	71.55	64.91
	11.00 p.m.	30.11	46.58	46.26	48.03	44.21	40.13
5.06.87	7.00 a.m.	30.11	46.48	45.92	47.54	43.61	39.50
	10.00 a.m.	37.38	53.88	52.40	53.60	48.65	43.56
	0.00 a.m.	45.08	61.78	60.25	61.79	56.14	50.32
6.06.87	4.00 a.m.	60.70	75.71	73.77	75.64	68.59	61.58
	9.00 a.m.	71.43	84.84	83.63	86.53	79.11	72.39
	1.00 p.m.	54.56	70.52	70.26	73.31	67.60	61.72
	6.00 p.m.	46.89	63.11	62.67	65.23	60.06	54.56

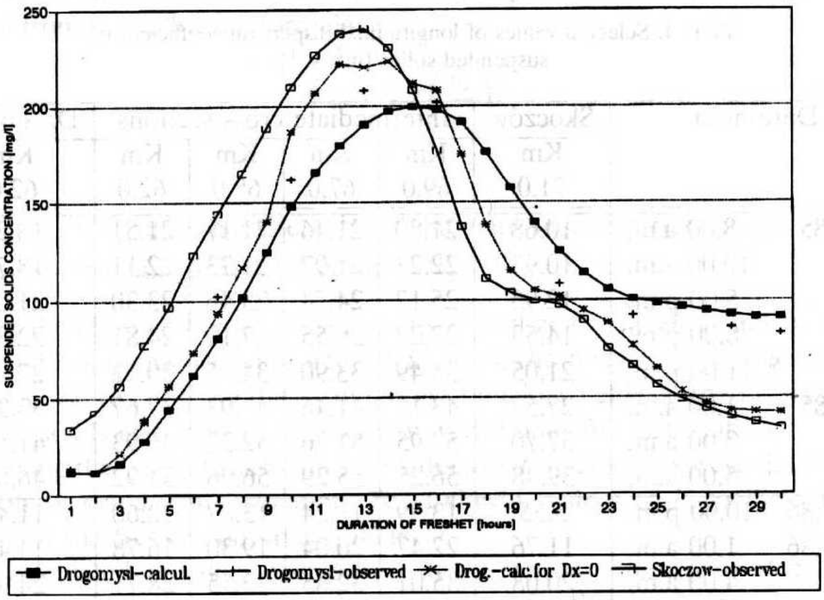

Fig. 1. Distribution of suspended solids freshet No. 1 02–03 June 1985

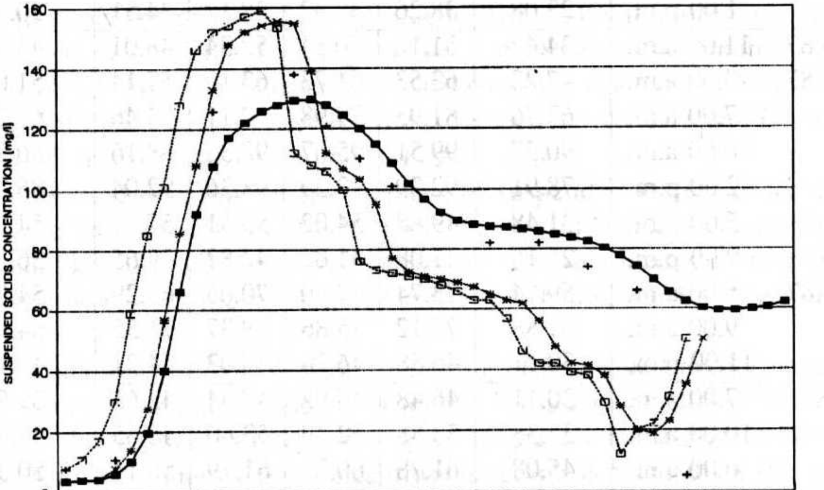

Fig. 2. Distribution of suspended solids freshet No. 2 20–30 December 1986

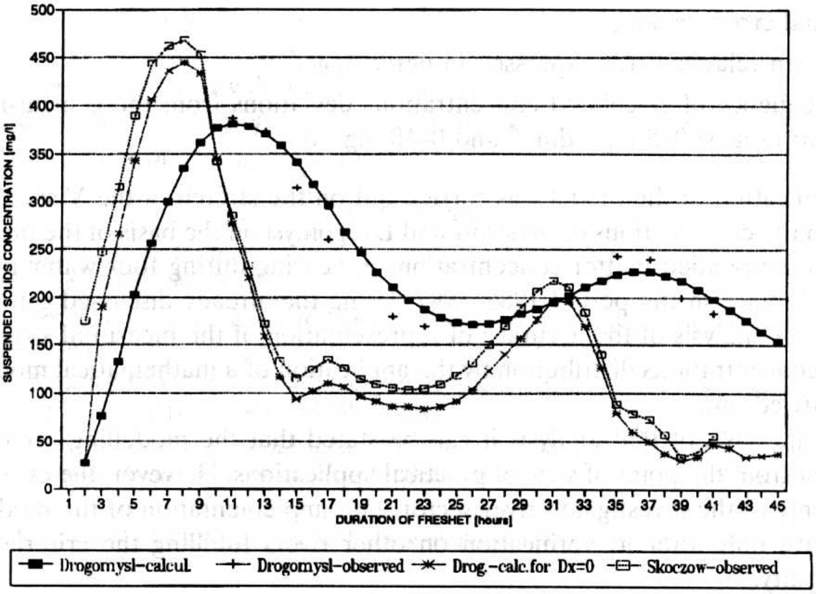

Fig. 3. Distribution of suspended solids freshet No. 3 21–23 May 1987

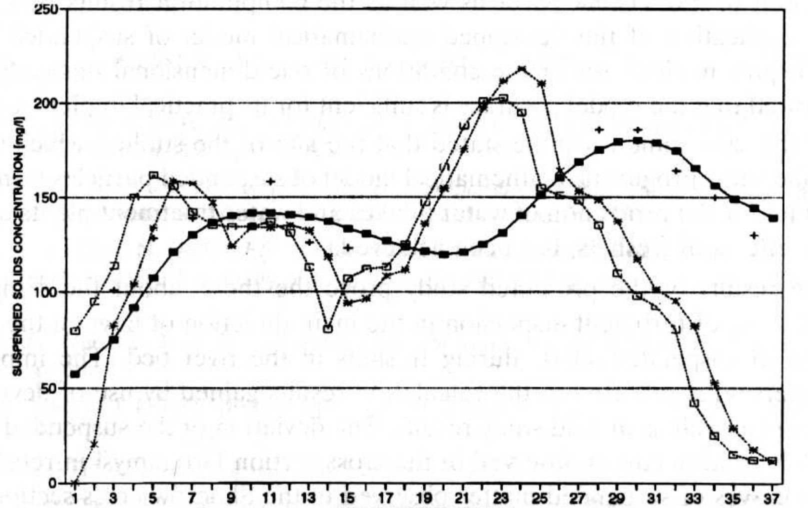

Fig. 4. Distribution of suspended solids freshet No. 4 05–06 June 1987

- mean absolute deviation of the calculated results from the measured in the final cross section;
- mean relative error expressed in percentage;
- frequency of calculated concentrations deviations from those measured in two ranges: 0–5 $mg \cdot dm^{-3}$ and 0–10 $mg \cdot dm^{-3}$.

The verification of the model was carried out on the stretch of the Vistula River between the cross sections of Skoczów and Drogomyśl on the basis of the measurements of suspended matter concentrations appearing during four water freshets that took place in the period 1985–1987. Using the already discussed estimation criteria, an analysis of the accuracy of representation of the measured suspended matter concentrations distribution by the application of a mathematical model has been carried out.

On the basis of that analysis it can be stated that the modelling accuracy is sufficient from the point of view of practical applications. However, the estimation refers only to the investigated river sector. Full implementation of the model can take place only after its verification on other rivers fulfilling the criteria of its applicability.

9. Conclusions

1. The results of field studies carried out in the years 1985–1987 in the selected section of the Vistula River as well as the computation results performed by application of the developed mathematical model of suspended solids transport in river, under the conditions of one-dimensional unsteady flow, showed that the model accuracy is sufficient for its practical implementation.
   At the same time it can be stated that the aim of the studies, which was to elaborate a prognostic mathematical model of suspended particles transport, useful for the protection of water intakes and water treatment plants against the effects of freshets, has been achieved.
2. The results of the presented study prove the thesis about the significant influence of turbulent dispersion in the main direction of flow on the transport of suspended solids during freshets in the river bed. The impact of dispersion is reflected in the calculation results gained by use of developed model as well as in field study results. The deviation of the suspended solids concentration curves observed in the cross section Drogomyśl in relation to the curves of suspended matter observed in the Skoczów cross section confirms the significance of longitudinal dispersion for prognosing the sediment transport.
3. The experimental estimation of the dispersion coefficients of suspended solids proved the experience of other authors that the values of these coefficients, in accordance with Reynolds' hypothesis, are close to the values

of dispersion coefficients for dissolved substances. This conclusion refers to conditions in which the study has been carried out: characteristics of the investigated river stretch as well as flows and types of suspended matter transported in it. It will be of great advantage to test the validity of this conclusion in other objects as it could contribute to the expansion of practical applicability of the model elaborated.

References

Bishop A. A., Simons D. B., Richardson E. V. (1965), Total bed material transport, *J. of Hydraulics Engineering, ASCE,* No. 91 HY2.

Boczar J. (1980), Formulas for modelling the processes of pollutants dispersion and transformation in rivers (in Polish), *Prace Naukowe Politechniki Szczecińskiej,* No. 148, Szczecin.

Brański J., Kondzielski A. (1985), *Evaluation of the sediment mass transport distribution along Vistula River* (in Polish), Manuscript in IMGW Warsaw.

Ciepielowski A., Dąbkowski L., Mordziński S., Skibiński J. (1968), *Studies on river sediment movement in the backwater zone of the Sulejów Reservoir on Pilica River* (in Polish), SGGW-AR, Warszawa.

Coleman N. L. (1980), Velocity profiles with suspended sediment, *J. of Hydraulic Research,* Vol. 19, No. 3.

Dąbkowski L., Skibiński J., Żbikowski A. (1982), *Hydraulic principles in water-melioration designing* (in Polish), PWRiL, Warszawa.

Dębski K. (1939), On transport and settling of alluvial material in Vistula River bed (in Polish), *Gospodarka Wodna*, No. 2.

Dębski K. (1946), Allowable velocity and Tractive force in Vistula River bed (in Polish), *Gospodarka Wodna,* No. 3.

Dębski K. (1957), *Regulation of rivers, Part I–Principles of designing* (in Polish), SGGW (editor), Warszawa.

Dresnack R., Dobbins W. E. (1968), Numerical analysis of BOD and DO profiles, *J. of the Sanitary Engineering Division, ASCE,* No. SA5.

Einstein H. A. (1950), *The bed load for sediment transportation in open channel flow,* U. S. Department of Agriculture, Soil Conservation, Technical Bulletin, No. 1028.

Einstein H. A., Chen N. (1955), *Effects of heavy sediment concentration near the bed on velocity and sediment distribution,* University of California, Institute of Engineering Resources, Report No. 8.

Gerald C. F., Wheatley P. O. (1986), *Applied numerical analysis,* Addison-Wesley Publishing Company, London.

Gładki H., Myczka J. (1968), Modern equations for sediment movement in rivers (in Polish), *Czas. Techn.,* No. 7B (119), Kraków.

Graf W. H. (1971), *Hydraulics of sediment transport,* McGraw-Hill Book Company.

Hurst H. E. (1929), The suspension of sand in water, *Proc. of the Royal Society of London*, Series A, Vol. 157.

Jarocki W. (1957), *Sediment transport in flowing waters* (in Polish), Wydawnictwo Morskie, Gdynia.

Kalinske A. A. (1940), Suspended material transportation under non-equilibrium conditions, *Transactions of the American Geophysics Union*, Vol. 21.

Krenkel P. A., Novotny V. (1980), *Water quality managements,* Academic Press.

Laursen E. (1958), The total sediment load of streams, *Journal of the Hydraulic Division, ASCE*, Vol. 54, No. HY1, Proc. Paper 1530.

Pasławski Z. (1971), Intensity of sediment transport in Odra River about Słubice cross-section (in Polish), *Przegląd Geofizyczny*, No. 1 and 2.

Pin-nam Lin, Hsieh-wen Shen (1984), Two-dimensional flow with sediment by characteristic method, *Journal of Hydraulic Engineering, ASCE*, No. 5.

Rodi W. (1985), *Turbulence models and their applications in hydraulics*, IAHR Section on Fundamentals, Delft.

Rohussar L. L., Paal L. L. (1969) K voprosu koefficienta prodolnoj diffuzii v otkrytych vodotokach, *Mater. III Vsesoj. Simp. po voprosam samoociscenija vodoemov i smescenija stocnych vod.*, Tallin.

Rouse H. (1937), Modern conceptions of the mechanics of turbulence, *Transactions of the American Society of Civil Engineers*, Vol. 102.

Skibiński J. et al. (1981), *Analysis of the Dębski's method for determination of the free moving force in a river bed and the conception of its modification* (in Polish), Manuscript in The Expert Group of SITWiM NOT, Warszawa.

Skibiński J. et al. (1982), *Distribution of the free moving force along Vistula River* (in Polish), Ibid., Warszawa.

Zamarin E. A. (1948), *Transportujuscaja sposobnost otkrytych potokow*, Stroizdat, Moskwa.