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Application of Stratified Flow Model in Estimation of River Bottom Morphology

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Abstract

Previous papers showed that the model of stratified flow, which was originally invented by Meyer, could be applied to describe changes of river bottom. Enabling the selection of circulation areas, this model allows the including of *dead zones* in flow patterns, which occur in the river bottom cavern. The intensity of sediment transport and analysis of changes of the river bottom cavern was specified on the basis of Ackers-White's known method.

Notations

A – dimensionless parameter characterising the density stratification and water flow,

$a_{1n}, a_{2n}, b_n, c_{1n}, c_{2n}, d_{1n}, d_{2n}$ – development coefficients of function into the Fourier's series,

B – length of reservoir [m],

D – sediment diameter [m],

D_{gr} – dimensionless sediment diameter,

F_{gr} – dimensionless sediment mobility,

G_{gr} – dimensionless function of sediment transport,

H – depth of reservoir [m],

H_{tr} – transit stream depth [m],

K_x, K_y – eddy viscosity coefficients in the x and y axis' direction correspondingly [m^2/s],

n – exponent in the equation of sediment transport function,

q – elemental flow through the reservoir [m^2/s],

$s = \rho_s/\rho$ – sediment density by volume to water density ratio,
u_* – shear velocity [m/s],
$V_0 = q/H$ – average velocity [m/s],
V_1 – dimensionless horizontal component of velocity at the water surface in the inflow,
V_{sr} – average velocity in the transit stream [m/s],
V_x, V_y – components of flow velocity in the x and y directions [m/s],
$V_{\xi,}, V_\eta$ – dimensionless components of velocity correspondingly in the ξ and η directions,
$V_\xi^\infty(\eta)$ – distribution of dimensionless component of vertical velocity in the inflow,
X – dimensionless parameter of sediment transport rate,
η, ξ – axes of dimensionless co-ordinates' system,
$\eta_1 = y_1/H$ – dimensionless co-ordinate of reservoir's outflow cross-section location,
$\eta_2 = y_2/H$ – dimensionless co-ordinate of reservoir's inflow cross-section location,
$\eta_{tr}(\xi)$ – dimensionless interface area between the transit and circulating streams,
ξ_1 – dimensionless co-ordinate describing the reservoir's length,
τ_d – bottom shear stress [m^2/s],
τ_w – shear stress at the water surface [m^2/s],
ν – kinematic coefficient of water viscosity [m^2/s],
ρ – water density [kg/m^3],
ρ_1 – water density at the bottom [kg/m^3],
ρ_2 – water density at the water surface [kg/m^3],
ψ – dimensionless current function,
Ψ – function of current,
$\psi^\infty(\eta)$ – dimensionless current function in the inflow,
ω – intensity of sediment transport rate in the transit stream [N/sm],
Ω – function of rotation.

1. Introduction

The physical and mathematical description of morphological processes occurring in riverbeds – due to their complexity and diversity – is one of the most difficult problems, which we have to cope with when modelling the flows in rivers. The bottom wash-out phenomenon below the hydrotechnical structures, influence of hydraulic conditions of water flow upon the sediment erosion and accumulation downstream of these structures, belong to the least recognised problems. The authors hope that the presented model of the water and sediment flow in the river cavern can be applied in the future to describe the hydraulic conditions of local scour downstream the weir.

The elaborated model of sediment transport in the river bottom cavern uses the description of stratified flow according to Meyer (Meyer 1981) and the Ackers-White's method of sediment transport in rivers (Ackers, White 1973). The application of stratified flow model enabling the selection of circulation areas in the reservoir enabled to defining of flow *dead zones* appearing in the local scour.

The model presented was modified by inserting a changeable – along the researched river section – parameter A. It was assumed that the change of A can be caused by the change of density distribution in the flow area, as well as reservoir's depth or variable turbulence. This allowed – while solving the reverse problem – searching for such a function $A = A(x)$, that the assumed bottom profile could be obtained.

2. Phenomenon Analysis and Accepted Assumptions

The flow in the reservoirs under circumstances of vertical stratification of water density is analysed in this paper (it is assumed that this reservoir illustrates the cavern in the river bottom). The following assumptions and simplifications were made to describe the phenomenon mathematically:

- the steady motion in the wide reservoir with H depth and B length,
- the flow is treated as the flat one in the reservoir's vertical cross-section,
- in the reservoir there is a water density gradient – this varies from the ρ_2 value at the water surface to the ρ_1 value at the bottom,
- the field of stream line and the field of flow velocity, which were taken from the model of vertical circulation, constitute the initial conditions for hydraulic calculations of water flow and sediment transport,
- sediment transport rate intensity and analysis of river bottom shape changes in the caverns were specified on the basis of Ackers-White's method,
- the sediment composition is assumed to be steady in the evaluations,
- the waves' influence and – due to small sizes of the analysed reservoir – Coriolis force influence are neglected in the calculations.

The co-ordinates' system in the model was assumed as follows (Fig. 1):

- the abscissa (x) covers the reservoir's bottom line and is directed opposite to the main direction of flow,

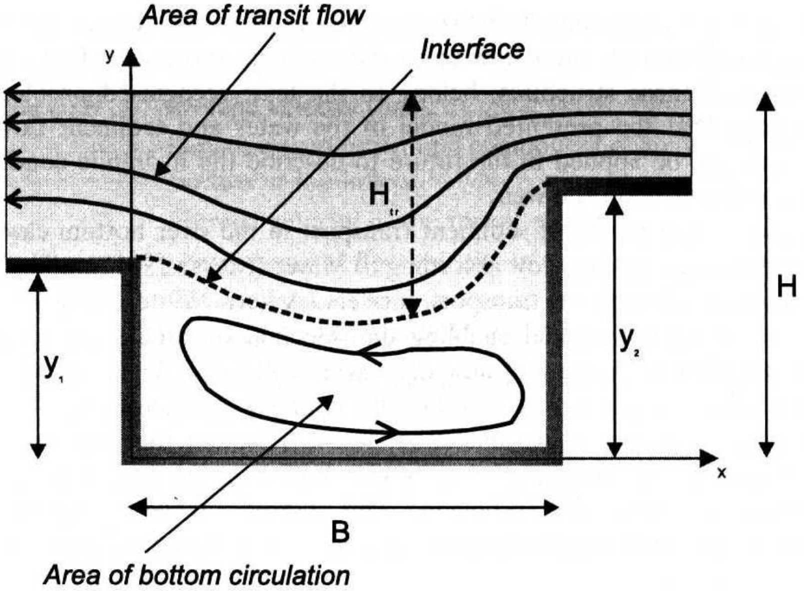

Fig. 1. Flow scheme in the rectangular reservoir

- the y-axis (y) covers the vertical reservoir's wall in the area of outflow and is directed upwards.

2.1. Model of Stratified Flow

A two-dimensional equation of turbulent flow was applied (Meyer 1981):

$$\begin{aligned}
\rho\frac{dV_x}{dt} &= \rho X - \frac{\partial P}{\partial x} + \frac{\partial}{\partial x}\left(\rho K_x \frac{\partial V_x}{\partial x}\right) + \frac{\partial}{\partial y}\left(\rho K_y \frac{\partial V_x}{\partial y}\right) \\
\rho\frac{dV_y}{dt} &= \rho Y - \frac{\partial P}{\partial y} + \frac{\partial}{\partial x}\left(\rho K_x \frac{\partial V_y}{\partial x}\right) + \frac{\partial}{\partial y}\left(\rho K_y \frac{\partial V_y}{\partial y}\right)
\end{aligned} \tag{1}$$

as was the equation of flow continuity:

$$\frac{1}{\rho}\frac{d\rho}{dt} + \frac{\partial V_x}{\partial x} + \frac{\partial V_y}{\partial y} = 0. \tag{2}$$

After introducing the stream function Ψ and rotation function Ω, the dimensionless co-ordinates η and ξ, dimensionless stream function ψ and dimensionless components of flow velocities V_ξ and V_η into the constitutive equations (1) and (2) as well as after further transformations, the equation of stratified flow finally takes the following form (Meyer 1981):

$$A \cdot \frac{\partial \psi}{\partial \xi} + \frac{\partial^2\left(\nabla^2 \psi\right)}{\partial \eta^2} = 0 \tag{3}$$

where: A – dimensionless parameter equal to:

$$A = \frac{\Delta\rho}{\rho_1}\frac{g H^3}{q}\frac{1}{\sqrt{K_y(K_x + K_y)}}. \tag{4}$$

Equation (3) was solved by adopting Fourier's series, achieving the following dimensionless form of stream function (Meyer 1981):

$$\begin{aligned}\psi(\xi,\eta) &= \psi^{\infty}(\eta) + \\ &+ \sum_{n=1}^{\infty}\left\{\left[a_{1n}\exp(d_{1n}\xi) + \left(a_{2n}\exp(-d_{2n}(\xi_1 - \xi))\right]\cdot\sin(\pi n\eta)\right\}\end{aligned} \tag{5}$$

and dimensionless velocity components:

$$\begin{aligned}V_\xi(\xi,\eta) &= V_\xi^{\infty}(\eta) + \\ &+ \sum_{n=1}^{\infty}\left\{\left[a_{1n}\exp(d_{1n}\xi) + \left(a_{2n}\exp(-d_{2n}(\xi_1 - \xi))\right]\cdot\pi n\cos(\pi n\eta)\right\},\end{aligned} \tag{6}$$

$$V_\eta(\xi,\eta) = -\sum_{n=1}^{\infty}\left\{\left[a_{1n}\exp(d_{1n}\xi) + \left(a_{2n}\exp(-d_{2n}(\xi_1 - \xi))\right]\cdot\sin(\pi n\eta)\right\} \tag{7}$$

where: ξ_1 – dimensionless co-ordinate describing the reservoir's length is equal to:

$$\xi_1 = \frac{B}{H}\sqrt{\frac{K_y}{K_x + K_y}}. \tag{8}$$

On the grounds of the former researches the rectangular distribution of velocities in the inflow and the parabolic one in outflow were assumed for calculation purposes. The following formulae (Meyer 1981) define the coefficients $a_{1n}, a_{2n}, d_{1n}, d_{2n}$ appearing in the equation (5) ÷ (7) for the assumed boundary conditions:

$$d_{1n} = \frac{A - \sqrt{A^2 + 4\pi^6 n^6}}{2\pi^2 n^2}, \quad d_{2n} = \frac{A + \sqrt{A^2 + 4\pi^6 n^6}}{2\pi^2 n^2} \quad n = 1, 2, \ldots \tag{9a, b}$$

$$a_{1n} = \frac{c_{1n} - c_{2n}\cdot\exp(-d_{2n}\cdot\xi_1) - b_n\left[1 - \exp(-d_{2n}\cdot\xi_1)\right]}{1 - \exp\left[-\xi_1(d_{2n} - d_{1n})\right]}, \tag{10a}$$

$$a_{2n} = \frac{c_{2n} - c_{1n}\cdot\exp(d_{1n}\cdot\xi_1) - b_n\left[1 - \exp(d_{1n}\cdot\xi_1)\right]}{1 - \exp\left[-\xi_1(d_{2n} - d_{1n})\right]}, \tag{10b}$$

where:

$$b_n = \frac{2(-1)^n}{\pi n} + \frac{4}{\pi^3 n^3}\left[(V_1+3) + (2V_1+3)\cdot(-1)^n\right], \tag{11}$$

$$c_{1n} = \frac{2(-1)^n}{\pi n} - \frac{2}{\pi^2 n^2}\frac{\sin(\pi n) - \sin(\pi n \eta_1)}{1-\eta_1}, \tag{12a}$$

$$c_{2n} = \frac{2(-1)^n}{\pi n} - \frac{2}{\pi^2 n^2}\frac{\sin(\pi n) - \sin(\pi n \eta_2)}{1-\eta_2}. \tag{12b}$$

The following parameters of the solution decide on the shape of the stream line for the assumed geometrical dimensions of the reservoir:

- dimensionless parameter A – including the vertical gradient of water density and flow conditions,
- dimensionless co-ordinate ξ_1 describing the reservoir's length,
- dimensionless wind dependent velocity V_1 at the water surface, coming from wind surface shear stress.

The influence of wind upon the circulation areas and water flow conditions in the reservoir were neglected, assuming the velocity $V_1 = -1.5$ (Meyer 1981).

2.2. Model of Sediment Transport

The intensity of sediment transport in the river was calculated on the basis of the known Ackers-White's method (Ackers, White 1973), thus its values depend upon the bottom shear velocity, average velocity, stream's depth and sediment parameters.

The evaluation procedure of Ackers-White's method includes determination of the following parameters:

- dimensionless D_{gr} diameter of sediment particles:

$$D_{gr} = D\left[\frac{g(s-1)}{\nu^2}\right]^{1/3}, \tag{13}$$

- coefficients of sediment motion: n, A, m and C:
  - n – exponent defining the kind of transported material:
    - $n = 0$ – bed sediment, $n = 1$ – floated sediment,
    - $n \in (0,1)$ – bed and floated sediment,
  - A – momentum of particle motion,
  - C – friction coefficient of sediment motion,
  - m – exponent,

for $D_{gr} \in (1, 60>$:

$$\left.\begin{aligned} n &= 1 - 0.56\log D_{gr} \quad \log C = 2.86\log D_{gr} - (\log D_{gr})^2 - 3.53 \\ A &= \frac{0.23}{\sqrt{D_{gr}}} + 0.14 \quad m = \frac{9.66}{D_{gr}} + 1.34 \end{aligned}\right\} \tag{14}$$

for $D_{gr} > 60$ parameters are constant: $n = 0.0$, $A = 0.17$, $C = 0.025$, $m = 1.5$,

- sediment mobility F_{gr}:

$$F_{gr} = \left[\frac{V_{sr}}{\sqrt{g D(s-1)}} \cdot \frac{1}{\sqrt{32}\log\frac{\alpha H_{tr}}{D}}\right] \cdot \left[\frac{u_*}{V_{sr}}\sqrt{32}\log\frac{\alpha H_{tr}}{D}\right]^n \tag{15}$$

- function of sediment transport G_{gr}:

$$G_{gr} = C\left(\frac{F_{gr}}{A} - 1\right)^m, \tag{16}$$

- dimensionless parameter of sediment transport rate X:

$$X = \frac{sD}{H_{tr}} G_{gr}\left(\frac{V_{sr}}{u_*}\right)^n, \tag{17}$$

- sediment transport intensity in flow Q:

$$\omega = X\rho g Q. \tag{18}$$

Hydraulic parameters of river water flow, i.e. main stream's depth $H_{tr}(\xi)$, average velocity $V_{sr}(\xi)$ and shear velocity $u_*(\xi)$, which are necessary to calculate the intensity of sediment transport rate carried by the transit stream, were evaluated by applying – according to the following formulae – the field of stream line as well as the field of horizontal component of flow velocity, which were achieved from the model of stratified flow:

- interface between transit flow and circulating $\eta_{tr}(\xi)$ from the condition: $\psi(\xi, \eta_{tr}) = 0$,
- transit stream's depth: $H_{tr}\ \xi) = (1 - \eta_{tr}(\xi)) \cdot H$,
- average velocity of transit stream: $V_{sr}(\xi) = V_0 \int_{\eta_{tr}}^{1} V_\xi d\eta$,
- shear velocity of transit flow at the interface: $u_*(\xi) = \sqrt{K_y \frac{dV_x}{dy}}$.

2.3. Analysis of Eddy Viscosity Coefficients

Practical application of the suggested model requires the values of eddy viscosity coefficients to be specified both in vertical K_y and horizontal K_x direction so that they could include the water flow conditions occurring in the modelled river section. In order to do so, the eddy viscosity coefficients were made dependent on the hydraulic flow parameters, inter alia average velocity to shear velocity ratio and elemental flow intensity.

Introducing the Boussinesq's hypothesis into the equations of turbulent motion and defining the shear stress $\tau_x(y)$ according to the Prandtl's formula concerning the mixing way, we obtain as follows:

$$\tau_x(y) = \rho K_y(y)\frac{dV_x}{dy}. \tag{19}$$

However, it can also be assumed (Meyer 1985), that vertical turbulent stresses $\tau_x(y)$ get changed linearly – from the τ_d value at the bottom to the $-\tau_w$ value at the water surface. If the wind influence upon the flowing water ($\tau_w = 0$) is neglected, the following will be obtained:

$$\tau_x(y) = \tau_d\left(1 - \frac{y}{H}\right). \tag{20}$$

The comparison of (19) and (20) relationships enables specifying the relation between the K_x, K_y eddy viscosity coefficients and river water flow conditions. In further analysis it is very convenient to assume that the K_y viscosity coefficient is – as in the flow model – constant and proportional to the elemental q flow according to the formula:

$$K_y(y) = K_y = \kappa q. \tag{21}$$

Assuming this, the vertical distribution of water velocities can be described as follows:

$$V_x(y) = \frac{\tau_d}{\rho\kappa q}\left(y - \frac{y^2}{2H}\right). \tag{22}$$

Integrating the velocity $V_x(y)$ by depth we obtain the elemental flow intensity q:

$$q = \int_0^H V_x(y)dy = \frac{1}{3}H^2\frac{\tau_d}{\rho\kappa q}, \tag{23}$$

hence:

$$\tau_d = 3\frac{\rho\kappa q^2}{H^2}. \tag{24}$$

Bottom shear stress τ_d can be described – according to Du Boys' formula – also as:

$$\tau_d = \gamma H I, \tag{25}$$

where: I – hydraulic slope equal to:

$$I = \frac{q^2}{c^2 H^3}. \tag{26}$$

Comparison of relationships (24) and (25) allows the calculating of the κ coefficient as:

$$\kappa = \frac{1}{3}\frac{g}{c^2} \tag{27}$$

obtaining finally:

$$K_y = \frac{1}{3}\left(\frac{u_d}{V_{sr}}\right)^2 \cdot q. \tag{28}$$

The formulae (28) describing the relation between the coefficient of eddy viscosity K_y and flow conditions was determined on the assumption that this coefficient is constant in the vertical direction. In the reservoir with the finite length the formula (28) should be written in the generalised form as:

$$K_y = \frac{1}{a_n}\left(\frac{u_d}{V_{sr}}\right)^2 \cdot q, \tag{29}$$

where: a_n – numerical coefficient.

The eddy viscosity coefficient in the horizontal K_x direction can be defined – with a good approximation and basing on former researches (Coufal, Meyer 1999) – according to the following relationship:

$$K_x = \left(\frac{u_d}{V_{sr}}\right)^{\chi} \cdot q, \tag{30}$$

where: χ – numerical coefficient, dependent on the reservoir's geometrical parameters.

The previous numerical evaluations and analysis of the obtained results (Pluta 2002) show that the a_n coefficient in formula (29) assumes values within the range of $0.5 \div 3.5$, while the χ coefficient in the (30) formula – within the range of $0.6 \div 1.0$.

3. Numerical Experiments

3.1. Influence of *A* Parameter on the Model Solution

The dimensionless parameter A, which is defined by the relationship (4), is the basic parameter deciding upon the solution of stratified flow. This parameter includes the intensity of density stratification and flow conditions. In the natural environment it can oscillate between 0 (no stratification) and around 10^6.

In the basic solution of the vertical stratification the model it is assumed that the parameter A is constant along the reservoir. In the general case the A value can vary due to the changes in density distribution in the flow area, changes of reservoir's depth or changeable turbulence. The motion equation (3) then assumes the following form:

$$A(\xi) \cdot \frac{\partial \psi}{\partial \xi} + \frac{\partial^2 \left(\nabla^2 \psi\right)}{\partial \eta^2} = 0. \tag{31}$$

The researches, which were carried out by Meyer (Meyer 1986), indicate that in the conditions of changeable parameter $A = A(\xi)$ the equation of the current function will take the following form:

$$\begin{aligned} \psi(\xi, \eta) &= \psi^{\infty}(\eta) + \sum_{n=1}^{\infty} \left\{ \left[a_{1n} \exp\left[D_{1n}(\xi) \right] + \right. \right. \\ &+ \left. \left. \left(a_{2n} \exp\left[-D_{2n}(\xi_1) + D_{2n}(\xi) \right] \right) \right] \cdot \sin(\pi n \eta) \right\}. \end{aligned} \tag{32}$$

where:

$$D_{1n}(\xi) = \int_0^{\xi} d_{1n}(\xi) d\xi, \quad D_{2n}(\xi) = \int_0^{\xi} d_{2n}(\xi) d\xi, \tag{33a, b}$$

$$d_{1n}(\xi) = \frac{A(\xi) - \sqrt{A(\xi)^2 + 4\pi^6 n^6}}{2\pi^2 n^2}, \quad d_{2n}(\xi) = \frac{A(\xi) + \sqrt{A(\xi)^2 + 4\pi^6 n^6}}{2\pi^2 n^2}. \tag{34a, b}$$

Depending on the $A = A(\xi)$ function, the analytical solution of equation (31) can be very difficult or even impossible. This problem can be solved numerically, dividing the flow field in the reservoir into vertical columns, in which the constant A parameter is assumed. In order to define the stream function, the basic solution that is described by the (5) ÷ (12) equations can be then used, remembering that the condition indicating that the stream functions are equal to each other at the border of neighbouring elementary areas must be fulfilled.

Fig. 2 shows the influence of parameter $A = A(\xi)$ that is changeable along the reservoir upon the stream line.

Practical calculations were carried out for the following flow $q = 3$ m^2/s as well as for the following geometrical parameters of the reservoir: $B = 40$ m, $H = 10$ m, $\eta_1 = y_1/H = 0.5$, $\eta_2 = y_2/H = 0.7$, $\xi_1 = 2.0$.

From the calculations carried-out it results that for the assumed flow geometry the A parameter influences the shape of forming circulation areas significantly. Changing the $A = A(\xi)$ function along the reservoir, it is possible to model the area of transit flow as well as circulating areas occurring in the reservoir's bottom zone.

3.2. Solution Optimisation for the Rectangular Reservoir

In the evaluation in point 3.1. the $A = A(\xi)$ function was assumed freely. The flow conditions in the reservoir, which are described by the K_x and K_y eddy viscosity coefficients, were not taken into consideration. Similarly, the dimensionless

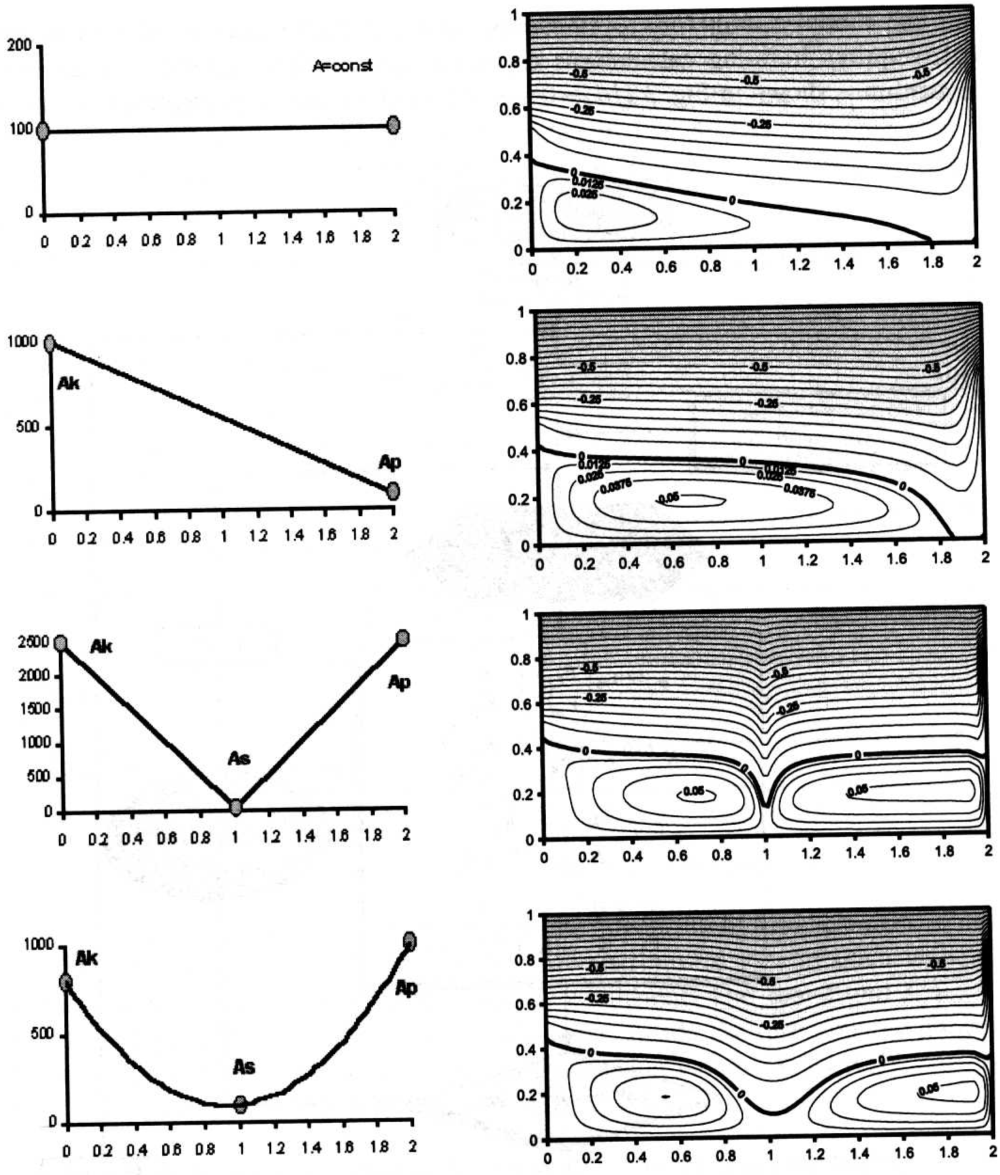

Fig. 2. Influence of the parameter $A = A(\xi)$ assumption on the stream line in a rectangular reservoir

reservoir's length ξ_1 was assumed a priori. It is necessary to introduce the (27) and (28) relationships into the description of the A parameter and ξ_1 coefficient in order to obtain the evaluated flow field corresponding with the real one.

The model parameter's optimisation under circumstances of density gradient, requires iterating calculations to be carried out. The simplified evaluative algorithm is shown in Fig. 3 ($jd = 0 \div n$, where n – number of elemental stripes).

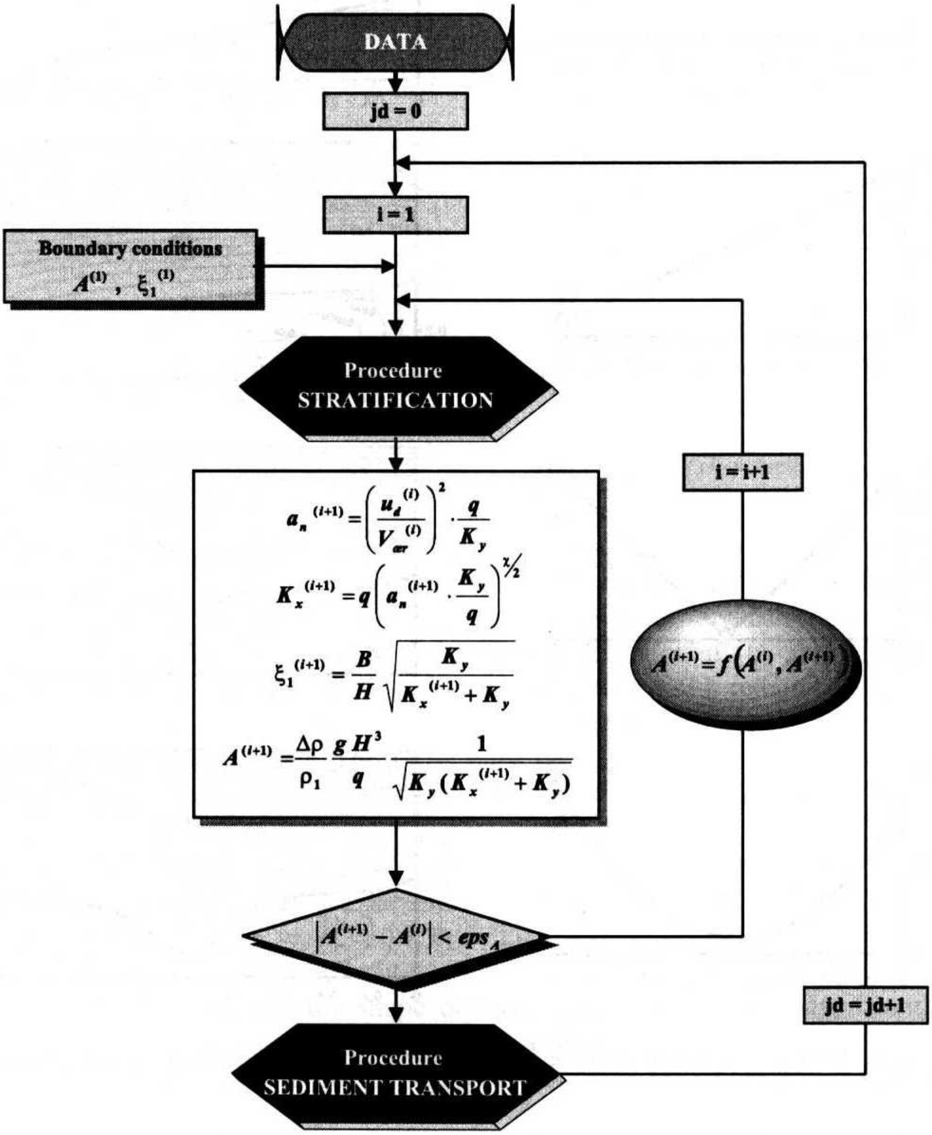

Fig. 3. Simplified evaluative algorithm

The suggested iteration enables the achieving of some solutions for both the assumed parameters: elemental flow intensity q, reservoir's geometrical dimensions H, B, η_1, η_2 and the given density gradient $\Delta\rho/\rho_1$, and afterwards defining the sediment transport rate intensity along the reservoir.

Some example optimisation results of eddy viscosity coefficient K_x, parameters A, ξ_1 and stratified flow solution are presented in Fig. 4. The following source data were assumed in the calculations: $H = 10$ m, $B = 40$ m, $\eta_1 = 0.5$, $\eta_2 = 0.7$, $q = 3$ m^2/s, $\Delta\rho/\rho_1 = 0.001$, $\kappa = 0.001$, $\chi = 2/3$.

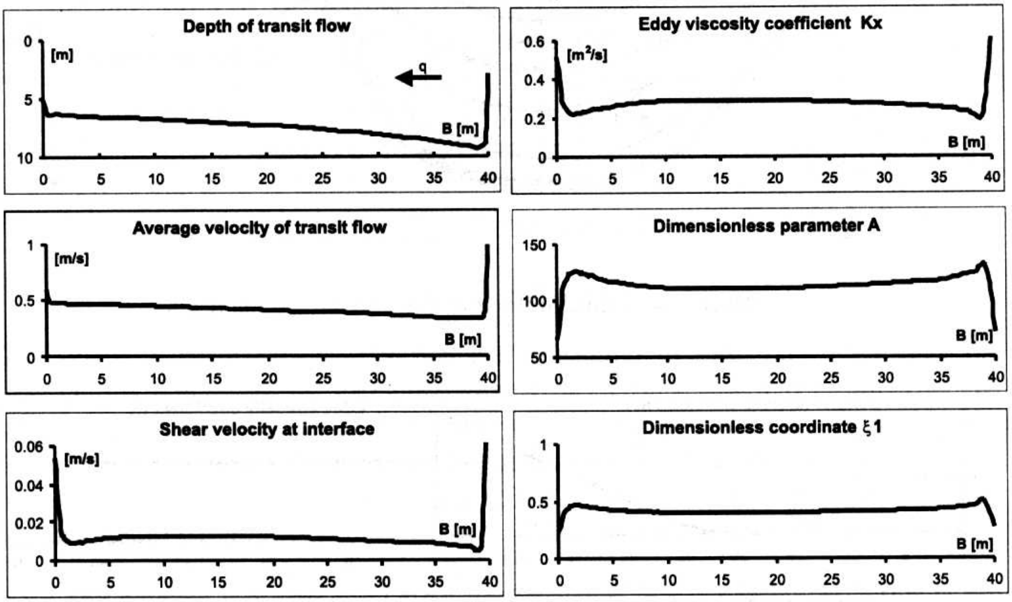

Fig. 4. Hydraulic calculations' results of flow in the rectangular reservoir

The results achieved indicate that due to the appearing of rapid changes of not only transit stream depth, but vertical velocity distribution V_ξ and shear velocity at the interface area – the K_x eddy viscosity coefficients and the A and ξ_1 parameters change definitely at both reservoir's edges. Inside the reservoir the abovementioned parameters settle, achieving the following values: $K_x = (0.26 \div 0.29)$ m^2/s, $A = (110 \div 115)$ and $\xi_1 = (0.40 \div 0.45)$.

3.3. Solution Optimisation for Reservoir with Changeable Depth

In order to calculate the water flow through reservoir with changeable depth, one can use the method of flow area digitisation into vertical columns (Fig. 5) presented in point 3.1, assuming that the change of function $A = A(\xi)$ results from the reservoir's changeable depth $H = H(\xi)$. This problem can be put inversely – knowing the shape of the reservoir's bottom, the optimisation of function $A = A(\xi)$ can be carried out.

Some examples of calculation results – for the assumed function describing the reservoir's bottom – are presented in Fig. 6. The following source data were

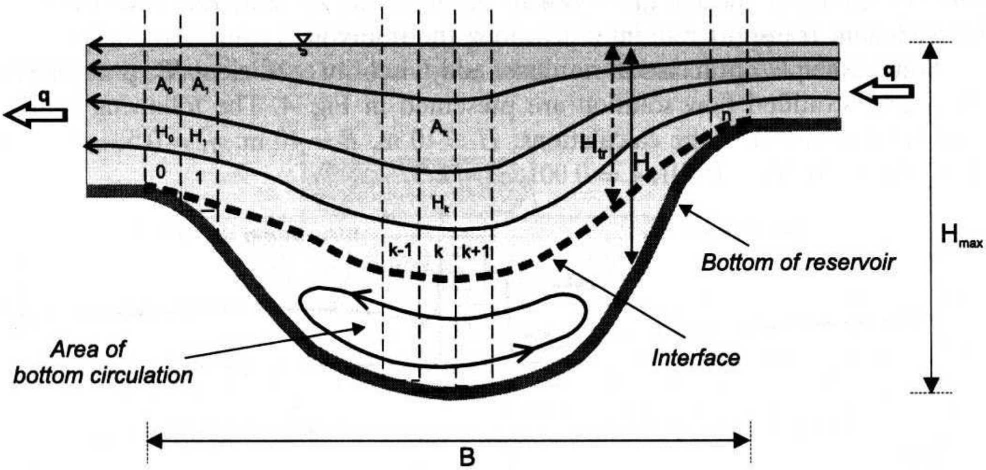

Fig. 5. Water flow scheme in the reservoir with changeable depth

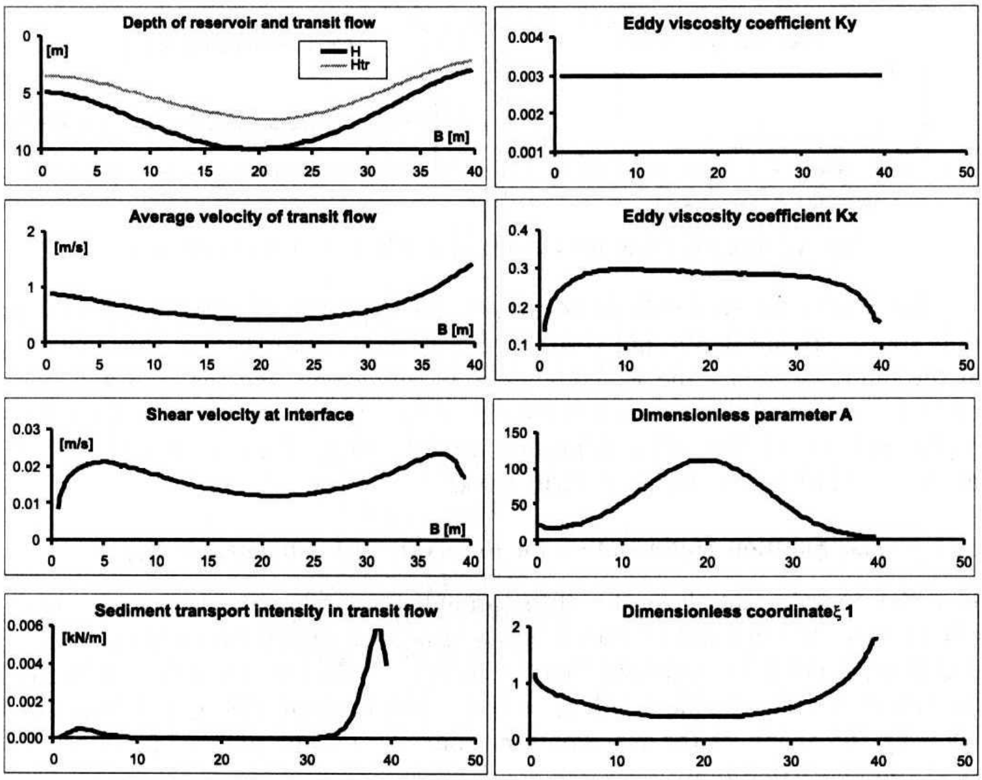

Fig. 6. Hydraulic calculations' results of flow in the reservoir with changeable depth

taken for the calculations: $H_{\max} = 10$ m, $B = 40$ m, $\eta_1 = 0.5$, $\eta_2 = 0.7$, $q = 3$ m^2/s, $\Delta\rho/\rho_1 = 0.001$, $\kappa = 0.001$, $\chi = 2/3$. in order to describe the shape of the reservoir's bottom, the parabola of the second degree was applied.

The comparison of model calculations' results, which were obtained for both the rectangular (Fig. 4) and parabolic reservoir (Fig. 6) shows how the reservoir's shape determines the flow conditions through it.

The intensity rate of sediment transport, which is carried by the transit flow and specified by the Ackers-White's method, is greatest at the reservoir's edges, where are the greatest flow and shear velocities. In the reservoir's centre part the quantity of transported material is significantly smaller. The evaluated values should be treated as the maximum sediment transport rate that can be transported in the given conditions. In order to conserve the continuity of sediment transport rate, it is necessary to include sediment material sorting in the calculations.

3.4. Solutions' Survey

The selected calculation results that are presented in Fig. 7 illustrate how the flow field is influenced by: elemental flow q, reservoir's length B (conserving the same shape) and depth $H_{\max}$ (parameters $\eta_1 = 0.5$, $\eta_2 = 0.7$ are constant). Due to different reservoir widths, in the diagrams the modelled H_{tr}, K_x, A, ξ_1 values were linked with the numbers of succeeding evaluative cross-sections ($n = 200$). The results obtained show that:

- the smaller the elemental flow q, the bigger the A parameter – this is not a strictly inversely proportional relationship, because – as results from the formula (4) – the change of A is also affected by the changeable H depth and changeable K_x, coefficient;
- the reservoir's length has less influence on the A parameter, however, the dimensionless length ξ_1 changes distinctly – according to the (8) formula,
- the change of reservoir depth visibly affects the change of the A parameter (the increase of $H_{\max}$ causes the increase of A) as well as the ξ_1 parameter – the reverse relation.

4. Conclusions and Program of Further Research

The paper presents the model of sediment transport in the river bottom cavern. This model uses both the description of stratified flow according to Meyer, as well as the method of sediment transport calculation according to Ackers-White, which was verified many times for the conditions of the Lower Odra River.

The model presented was modified by inserting the changeable – along the examined river section – parameter A. It was analysed how the function scheme $A = A(x)$ affects the change of river bottom geometry, water flow conditions and

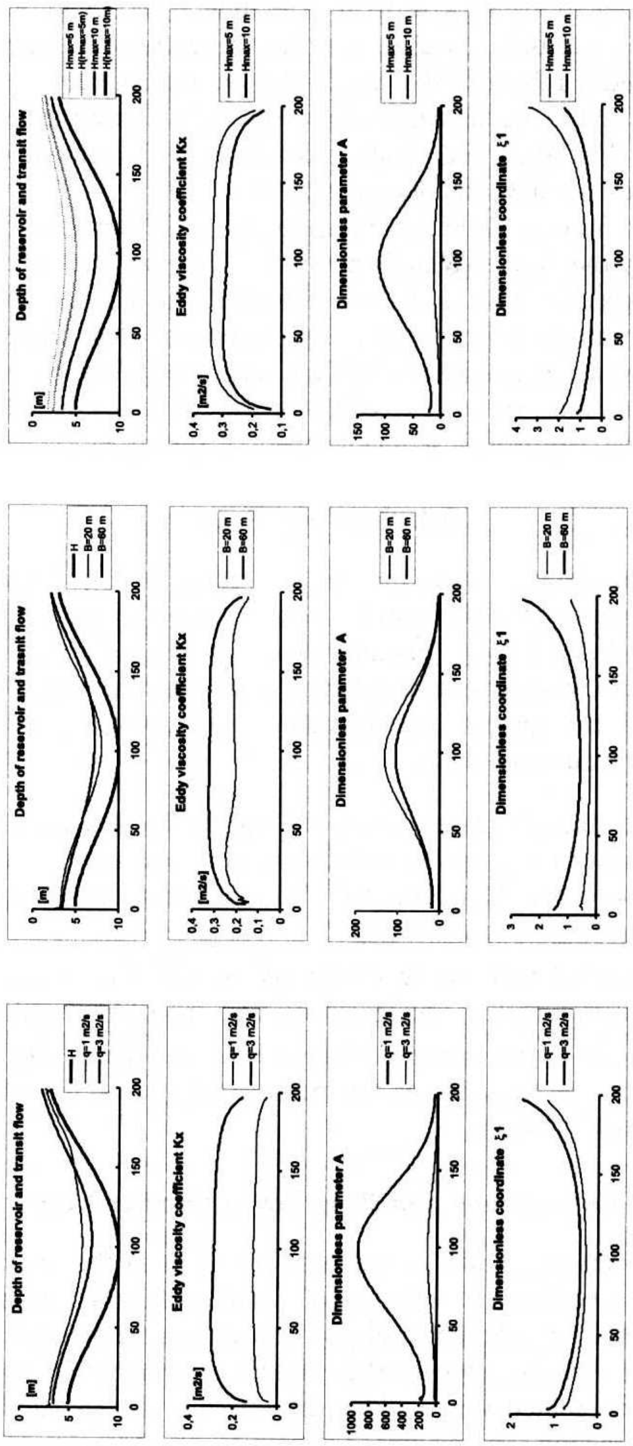

Fig. 7. Hydraulic calculations results of flow in the reservoir with changeable depth

sediment transport. The function $A = A(x)$ was also optimised so that the assumed bottom profile could be obtained, as the reverse problem.

In the model of vertical stratification it is very difficult to specify the eddy viscosity coefficient correctly so that they could precisely reflect the flow conditions in the reservoir. Having the practical application of calculation results in mind, in this paper one put forward the optimisation procedure for the flow solution through the reservoir under circumstances of vertical stratification, defining the real values of K_x and K_y coefficients.

The presented method enables calculation of the intensity of the sediment transport rate in the water flow through the cavern. Conservation of sediment continuity in the inflow (at the weir entrance) and in the cavern, will allow future modelling of the bottom formations.

The program of further researches provides for the application of the presented model to describe the hydraulic conditions of local scour formation in the lower position of the weir.

References

Coufal R., Meyer Z. (1999), Wind friction coefficient analysis in river flow, *7th Conference Problems of Hydroengineering, Researches of Institute of Geotechnical Engineering and Hydrotechnic at the Technical University of Wrocław*, Wrocław (in Polish).

Liriano S., Day R., White W. (2002), Scour culvert outlets as influenced by the turbulent flow structure, *Journal of Hydraulic Research*, Vol. 40, No. 3.

Meyer Z. (1981), Vertical circulation in the reservoir caused by selective approach, *Researches of Technical University in Szczecin No. 178*, Szczecin (in Polish).

Meyer Z. (1985), Mechanism of bottom density wedges, *Archives of Hydrotechnics*, Vol. XXXII, part 2, PWN, Warszawa.

Meyer Z. (1986), Vertical Circulation in Density-Stratified Reservoirs, [in:] *Encyclopaedia of Fluid Mechanics*, Vol. 2. Dynamics of Single-Fluid Flows and Mixing.

Meyer Z., Pluta M. (2001), Application of Stratified Model to Analysis of Sediment Transport in River Cavern, [in:] *Conference Materials on the Occasion of the 70th Anniversary of Prof. Wilde*, Gdańsk (in Polish).

Pluta M. (2001), Application of the Stratified Flow Model to the Description of the Sediment Transport in the River Cavern, *XXI School of Hydraulics, Contemporary Problems of Inland Water Hydraulics*, IBW PAN Gdańsk (in Polish).

Pluta M. (2002), Estimation of Eddy Viscosity Coefficients in the Model of Vertical Stratification, *X Scientific Seminar "Regional Problems of Environmental Protection in the Odra River Estuary"*, Międzyzdroje (in Polish).