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Analysis of Bottom Position Changes in a Lowland River on the Basis of Sediment Transport

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Abstract

The paper present an analysis of changes in the Odra River bed position, which is based upon the evaluations of intensity of the sediment transport rate, which is specified by the modified Ackers-White's method. The case of flow between groins and the change of hydraulic conditions has been presented for the newly designed longitudinal dam. The analyses were carried out for different flow intensities, comparing the results achieved with the measurement in the Hohensaaten–Bielinek section.

Notations

$A(H)$ – area of river bed cross section at the specified depth [m^2],
B – width of river bed [m],
D – sediment grain (or fraction) diameter [m],
D_0 – median defining sum of products giving percentage contents and size of grains for the specified fractions [m],
D_z – substitutive diameter [m],
H – river depth in cross section [m],
I – river slope,
n_s – coefficient of bottom roughness according to Manning [m$^{-1/3}$s],
p_i – percentage contents of i fraction,
Q – water flow intensity in the analytical cross section [m^3/s],
s – sediment density to water density ratio,
u_* – shear velocity [m/s],
υ – water flow velocity in cross section [m/s],
Δx – distance between the succesive analytical cross sections [m],
ρ – water density [kg/m^3],
ω – sediment mass in cross section [N/s].

1. Evaluative Method

In this elaboration, in order to analyse the changes in the sediment transport rate in the river, the method, published by Peter Ackers and William Rodney White in 1973, has been applied. This method is based upon the assumption that the change of the bottom position is due to the difference of the sediment transport rates between the analysed cross-sections. The sediment transport rate in the cross-section is described by the hydraulic parameters: average flow velocity in the cross-section, shear stress velocity at the bottom, depth, granulometric composition and sediment density.

The average flow velocity to the shear stress velocity ratio is the basic factor influencing the value of the sediment transport rate. In the original method the logarithmic distribution of vertical flow velocities in the cross-section according to Prandtl, as well as the definition of the shear stress velocity was assumed, which – after transformations – determines the average flow velocity to the shear stress velocity ratio for the phase of the developed turbulence of flow over a rough surface in a following form:

$$f_0 = \frac{v_0}{u_*} = \sqrt{32}\log\frac{12,3H}{K_s} = \sqrt{32}\log\frac{\alpha H}{D}. \tag{1}$$

Introducing some dimensionless parameters and concept of the dimensionless grain (elements) diameter, the description of the total bed material load can be written in the form of an exponential equation, where the exponent specifies the kind of transport:

$$G_{gr} = \frac{XH}{sD}\left(\frac{u_*}{v_0}\right)^n. \tag{2}$$

The sediment transport rate ω, which is carried by flow Q can be written as the function of the dimensionless parameter of the sediment transport rate X as:

$$\omega = X\rho g Q, \tag{3}$$

where:

$$X = \frac{sD}{H}G_{gr}\left(\frac{v_0}{u_*}\right)^n, \tag{4}$$

$$X = \frac{sD}{H}G_{gr}\left(\frac{v_0}{u_*}\right)^n, \tag{5}$$

$$F_{gr} = \left[\frac{v_0}{\sqrt{gD(s-1)}}\cdot\frac{1}{\sqrt{32}\log\frac{\alpha H}{D}}\right]\cdot\left[\frac{u_*}{v_0}\sqrt{32}\log\frac{\alpha H}{D}\right]^n. \tag{6}$$

The average change of the riverbed bottom between the cross-section in time Δt can be defined as:

$$\Delta d_{i,i-1} = \frac{\omega_i - \omega_{i-1}}{\gamma_0 B_{sr}\Delta L_{i,i-1}}\Delta t. \tag{7}$$

The evaluative procedure of the original Ackers-White's method is as follows: for the determined values of the grain diameter D (D_{35} for materials with various grains), value s, average flow velocity v_0, shear stress velocity u_* and depth H the following values are defined:

- value of the dimensionless sediment diameter D_{gr} on the basis of the relationship:

$$D_g r = D \left[\frac{g(s-1)}{\nu^2} \right]^{\frac{1}{3}} . \tag{8}$$

- coefficients of sediment movement: n, A, m and C as functions of the value D_{gr}:

  a) for $D_{gr} \leq 1$ – suspended load:
  $n = 1.0 \quad m = 0, \quad A = 0, \quad C = 0,$

  b) for $1 < D_{gr} \leq 60$ (the area of transitory movement around the particles) bed load and suspended load:

$$m = 9.66/D_{gr} + 1.34,$$

$$n = 1 - 0.56 \log D_{gr},$$

$$A = 0.23/\sqrt{D_{gr}} + 0.14,$$

$$\log C = 2.86 \log D_{gr} - (\log D_{gr})^2 - 3.53,$$

  c) for $D > 60$ (turbulent motion around the particles) – bed load, coefficient values are constant:
  $n = 0 \quad A = 0.17, \quad m = 1.50, \quad C = 0.025,$

- sediment mobility F_{gr},
- function of sediment transport G_{gr}.

The Ackers-White's model is the balance model, which specifies the total sediment transport rate. The changes of the river bottom position are defined on the basis of the sediment stream in cross-sections. This model does not take the bottom forms, which accompany changes of sediment transport rate into consideration. The authors are aware that the sediment transport rate is related to the turbulence development at the bottom: the more sediment is carried by river stream, the more intensive processes occur at the bottom.

The presented model of bottom position changes was verified by the field measurements in the Odra River estuary and along its middle course, after introducing modified velocity distribution, which includes the influence of shear stresses on the water surface. This model was applied in several particular cases: river-bed narrowing due to regulating structure, in the bridge cross-section, river bifurcation and hydraulic junction; pointing to its practical usage in engineering and water economy.

2. Examples of the Method of Application

2.1. Flow Between Groins

One-kilometre-long river section, which is limited by a pair of 200-m-wide wing dams, was taken for the analysis. The river water slope was assumed to be $I = 10^{-4}$, the roughness coefficient in the initial cross-section equal to 0.030, sediment composition $\{D_i,\ p_i\}$ and flow $Q = 400\ \mathrm{m^3/s}$. The flow stream between the dams was approximate trapezoid (Fig. 1 – dashed line). The consequence of such simplification is the linearly changeable riverbed width and occurrence of discontinuity point in the middle distance between the dams.

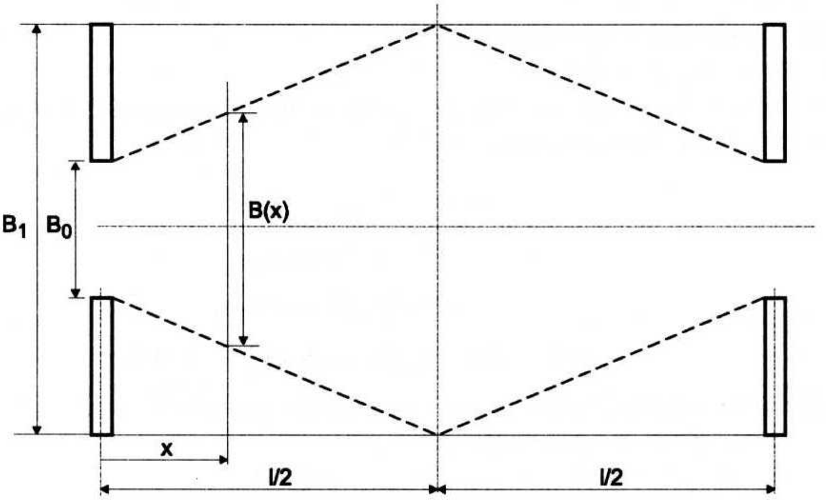


Fig. 1. Assumed diagram of river stream width changes between the dams

The evaluative procedure consists of the following stages: for the assumed hydraulic and geometrical values in the initial cross-section "0" the depth value is defined for the assumed roughness coefficient in the analytical cross-section "x"; the sediment transport rate in the cross-sections "0" and "x" is defined according to the modified Ackers-White's method; the relationship between the roughness coefficient and depth – for successive fractions, and the parameter optimisation of the roughness coefficient according to the relationship:

$$n_s^{(x)} = n_s^{(0)} \cdot \left(\frac{D_z^{(0)}}{D_z^{(x)}} \right)^{\frac{1}{6}} . \tag{9}$$

This analysis is presented graphically in Fig. 2. So-defined values satisfy the equation of the flow continuity in the successive cross-section, as well as the equation of sediment continuity for successive fractions

– sediment continuity:

$$\omega(x) = \omega\{p_i, D_i\}, \tag{10}$$

– optimisation of the roughness coefficient:

$$n_s = M\left(\frac{H}{D_z}\right)^{\frac{1}{6}}. \tag{11}$$

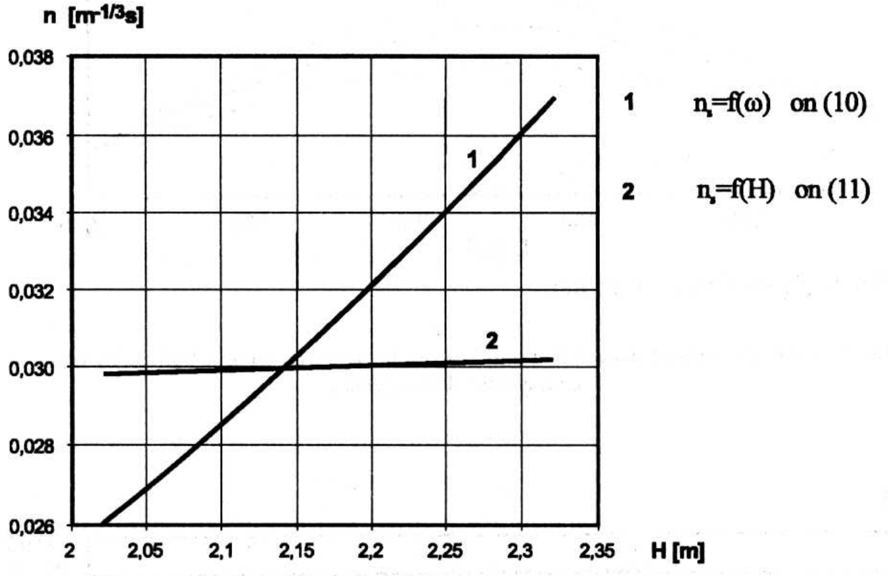


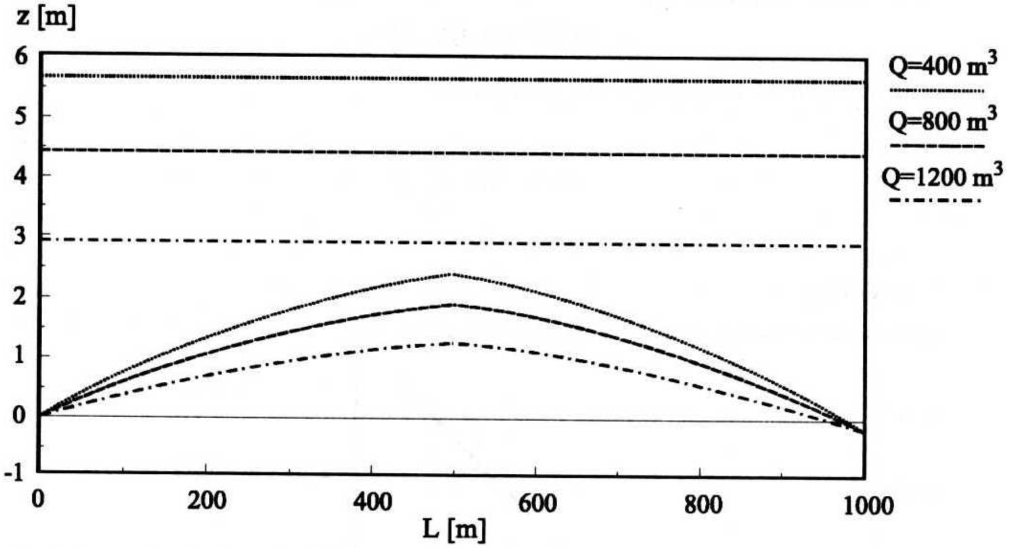
Fig. 2. Optimisation of roughness coefficient as the function of depth

The change of bottom position in the successive cross-section was specified on the basis of the energy conservation equation according to Bernoulli. Carrying out calculations for a total 20 cross-sections, the curves illustrating the bottom position and water level in the selected river section are drawn in the common co-ordinates' system.

The examples of evaluation results are shown in Figures 3a, 3b and 3c (according to (Coufal, Meyer 1996)).

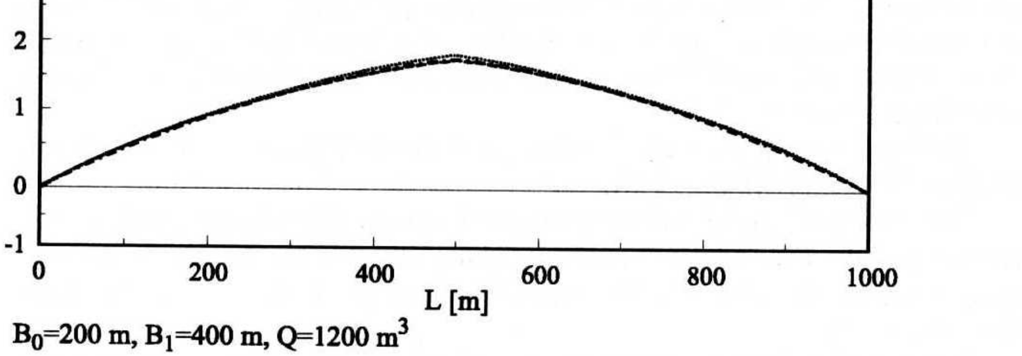
The numerical model was so constructed as to enable inserting any assumed geometry of the river section into the program, inserting the designed hydrotechnical structure and analysing the sedimentary changes in respect of changeable flow intensities.

The model calibration, which was carried out for average-approximated conditions for the Odra River section in the area of Hohensaaten-Bielinek, showed considerable convergence between the numerical simulations and the field measurements (dams-regulated section).



B_0=200 m, B_1=400 m, D=0,25 mm

Fig. 3a. Position changes of water level and bottom in the river section limited by dams at the changeable flow intensity



B_0=200 m, B_1=400 m, Q=1200 m^3

Fig. 3b. Position changes of water level and bottom in the river section limited by dams at the changeable riverbed width in the cross-section between the dams

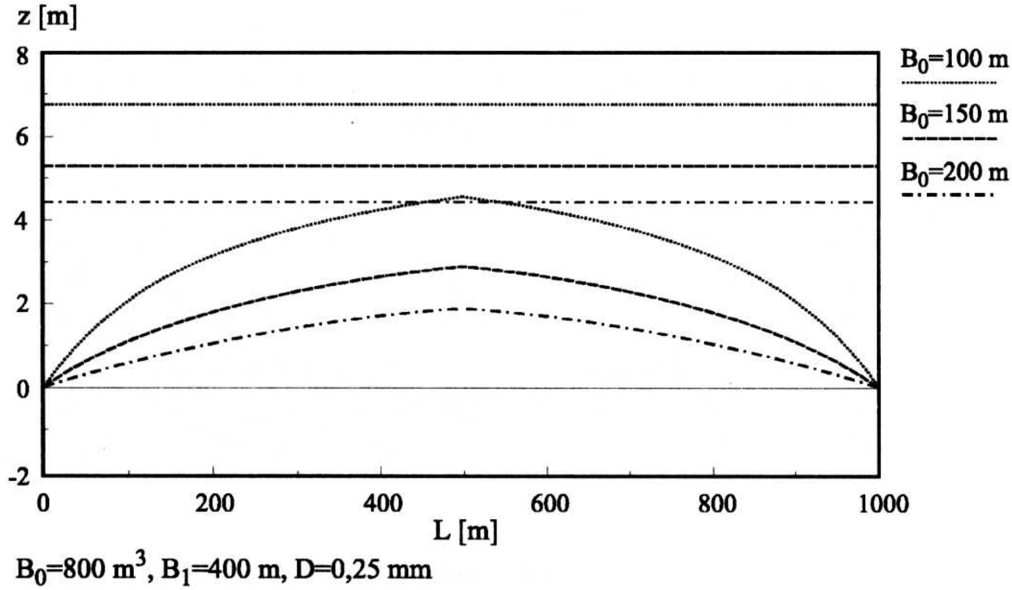


Fig. 3c. Position changes of water level and bottom in the river section limited by dams for the transported sediment with various substitutive diameters

In principle, all elements of the motion equations required to be recognised, calibrated and verified after the model had been created, starting with the elaboration of turbulence model in the river, through analysis and such generalisations of sediment characteristic that the substitutive (characteristic) diameters could offer the phenomenon dynamics in fully, finishing with the insertion of the real riverbed geometry to the model (both in cross-sections and in layouts), insertion of centrifugal forces influence upon the sediment transport rate, which is especially important in so-called river bends.

Also specified in the analyses was, how it is possible to model the passage of flood wave in the section in the area of the Bielinek and Widuchowa junction (flood wave passage in June 1997).

For the newly designed dam in the Hohensaaten-Bielinek section (Fig. 4), numerical simulations were carried out for flow intensities of 380, 480, 700 m^3/s, comparing them to structureless motion conditions. It was stated that the dam would make the flow concentrate and riverbed deepen a little, but would not cause considerable changes in the water level and that the longitudinal river slope would be stabilised.

Fig. 5 present an exemplary cross-section of the analysed section with newly designed longitudinal dam, for a flow intensity of 380 m^3/s.

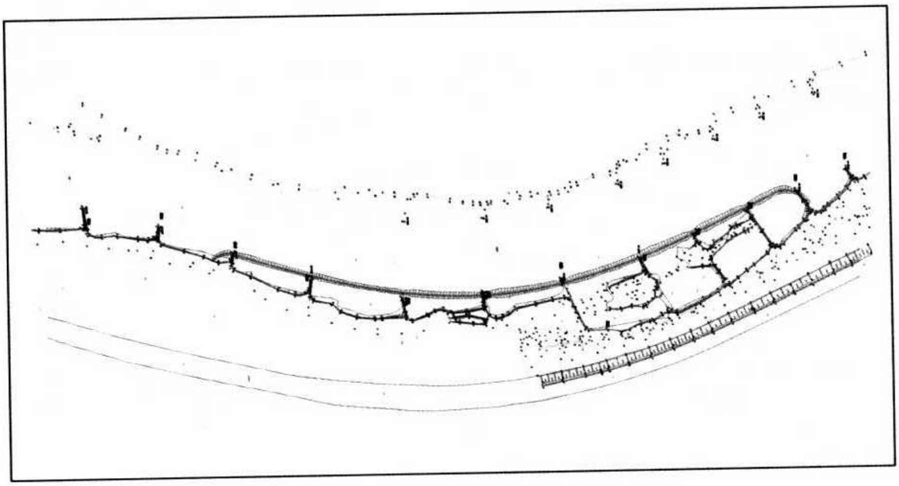


Fig. 4. The assumed Odra River section with changed regulating route in the form of a longitudinal dam

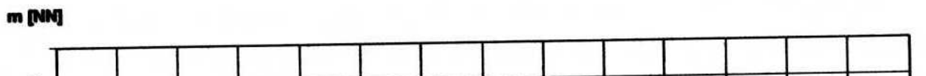


Fig. 5. The example printout of the analysis of the bottom changes in cross-section at km 68.60 of the Odra River

3. Conclusions

1. The present paper presents the application of a numerical model with which to analyse riverbed bottom changes. The model is based on the evaluations of the sediment transport rate in cross-section.
2. The basic advantage of the formulated mathematical model is that it can be used as a tool for forecasting river bottom changes, caused by a designed regulating structure, as well as for analysing the river bottom stability in any hydraulic conditions.
3. After being verified by a wide range of flow intensities and calibrating the constant values of local characters, this model can be applied to design changes of regulating route and hydrotechnical structures interchangeably with hydraulic models.

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