USPTTP01
Protection of wetland habitats and its interaction with regional development

USPTTP02
Impact of freshwater supply reservoirs on the river morphology and ecology at the upstream

USPTTP03
The role of urban development and river training structures in river bed erosion

USPTTP04
Flood control and management in a river-reservoir system with reservoirs in series

USPTTP05
Influence of river training structures on the flow hydrodynamics and river morphology

USPTTP06
Silting and grain sorting in freshwater supply reservoirs and the impact in the backwater region

USPTTP07
Flood protection and efficient management of wetland habitats through simulation

USPTTP08
Water quality in shallow lakes and the role of floodplain on filtering incoming nutrients

WARSAWA 2005
INSTITUTE OF GEOPHYSICS
POLISH ACADEMY OF SCIENCES

NATIONAL CENTER
FOR COMPUTATIONAL HYDROSCIENCE AND ENGINEERING
THE UNIVERSITY OF MISSISSIPPI

PUBLICATIONS
OF THE INSTITUTE OF GEOPHYSICS
POLISH ACADEMY OF SCIENCES

MONOGRAPHIC VOLUME

E-5 (387)

COMPUTATIONAL MODELING FOR THE DEVELOPMENT
OF SUSTAINABLE WATER-RESOURCES SYSTEMS IN POLAND

US-POLAND TECHNOLOGY TRANSFER PROGRAM
US-AID Award Number: EEE-G-00-02-00015-00

Editors:
Mustafa S. Altinakar, Włodzimierz Czernuszenko
Paweł M. Rowiński and Sam S.Y. Wang

WARSZAWA 2005
Forecasting of Fluvial Processes on the Skawa River Within Back-Water Reach of the Świnna Poręba Water Reservoir

Wojciech BARTNIK*, Kazimierz BANASIK**, Leszek KSIĄŻEK*, Artur RADECKI-PAWLIK* and Andrzej STRUŻYŃSKI*

*Department of Water Engineering, Faculty of Environmental Engineering and Land Surveying Agricultural University of Cracow Al. Mickiewicza 24-28, 30-059 Kraków, Poland www.kiw.ar.krakow.pl

**Department of Hydraulic Engineering and Environmental Recultivation Faculty of Engineering and Environmental Science, Warsaw Agricultural University ul. Nowoursynowska 166, 02-787 Warszawa, Poland e-mail: banasik@alpha.sggw.waw.pl

Abstract

The aim of the project is to model fluvial processes along the Skawa River reach within the influence of the back-water caused by the Świnna Poręba reservoir. The study was carried out using a set of the field measurements as well as computer simulations with CCHE2D model developed by the National Center for Computational Hydrosience and Engineering (NCCHE) at the University of Mississippi.

The field measurements were realized continuously between early spring 2003 and summer 2004. The field measurements consist of: longitudinal profile of the research reach, 31 research cross-sections, sieve curves for riverbed based on 12 freezing samples and 20 sieving samples and velocity profiles (in chosen 6 cross-sections). The numerical modelling part of the project focused on the prediction of water discharge changes under different water levels in the reservoir, bed elevation changes, shear stresses pattern, and many other hydrodynamic conditions along the research reach caused by the construction of the Świnna Poręba reservoir.

Numerical results obtained from the simulations with CCHE2D were also compared with ARMOUR and TRANS software developed at the Water Engineering Department at Agricultural University of Kraków.
1. Introduction

The construction of a reservoir in a river inevitably changes, or at least influences, the hydrodynamics of the flow as well as the fluvial processes in a river. A reservoir, which dams-up millions of cubic meters of water, must certainly influence the behavior of the river and the fluvial processes in its catchment. It is, therefore, an important task for river engineers to predict channel morphological changes and other hydraulics parameters such as hydraulic radius, velocity, shear stresses, flow resistance parameter, roughness and energy gradient and sediment transport after the construction of the reservoir. Another important issue is the prediction of the locations of the riverbed aggradation (deposition) and degradation (erosion) under the influence of back-water, which is controlled by the reservoir operation rules. In general, these tasks are carried out by using sophisticated computer models, which help to understand the fluvial processes and hydraulic parameters resulting from the changes in hydrodynamics conditions of the river due to the impoundment of water in the reservoir.

The word fluvial is a general term that refers to anything produced by the action of river (i.e. fluvial forms, fluvial processes fluvial systems and fluvial sediments) (Thomas and Goudie, 2000). At the same time, a model can be viewed as a selective approximation, which is obtained by elimination of incidental detail (Whittow, 1984). Modeling of fluvial processes, therefore, can be generally used in the context of allowing some interesting aspects of fluvial processes to appear in a generalized form.

As an initial step in searching for an adequate understanding of channel geometry changes, the variables and their interactions involved in the fluvial processes need to be identified. Variables for the alluvial river are classified as independent and dependent variables; that is, cause and effect. Those that are imposed upon the river by any source are independent variables or controlling variables, whereas those that result are dependent variables (Kennedy and Brooks, 1963). The river has no control over the independent variables but instead is controlled by such variables. Variables which we must consider are: the fluid property, sediment property and characteristics of flow system (they are morphological and hydraulic parameters), including water discharge, sediment discharge, channel width, flow depth, mean velocity, hydraulic radius, channel slope and friction factor.

One must understand that river engineering involves control and utilization of rivers for the benefit of mankind by means of river training, channel design, flood control, hydraulic structures design etc. When changing the river environment by constructing river engineering works (in the case of the project building a large reservoir) the engineer inevitably influences the river processes within the river catchment. In the present study, the changes in channel morphology, sediment transport and hydraulic parameters are analyzed, on the basis of field measurements, using the CCHE2D model from NCCHE, the University of Mississippi. Obtained results were
compared with ARMOUR and TRANS software developed at the Water Engineering Department at the Agricultural University of Kraków. The entire project work was set up in Polish Carpathians on the Skawa River.

2. Materials and methods

2.1. Research catchment

The investigated Skawa River is situated in the Polish Carpathians within the region called Beskidy (Fig. 1). The Skawa River catchment lies in the Carpathian flysch, where the streambed consists mainly of sandstone and mudstone bed-load pebbles and cobbles, which form a framework where the interstices are filled by a matrix of finer sediment. The Skawa cuts through an alluvial bed, mainly consisting of Quaternary and Holocene river gravels, sands and mudstones. Strong bank erosion is evident, especially along the left bank of the study reach. Many gravel-river bedforms were noticed within the investigated Skawa reach, such as point and middle bars. These free bed-forms migrate downstream, but occasionally fixed bars also occur. These are swept away during huge floods but tend to recover and build up at the same places they were previously found. Mostly, gravel bed-forms grow behind and in front of obstacles and are quite durable, particularly those situated on the riverbanks.

Some basic physical characteristics of the investigated stream are presented in Table 1.

<table>
<thead>
<tr>
<th>Variables</th>
<th>The Skawa River</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation [mm]</td>
<td>850</td>
</tr>
<tr>
<td>Catchment area [km²]</td>
<td>835</td>
</tr>
<tr>
<td>Max. catchment length [km]</td>
<td>44.4</td>
</tr>
<tr>
<td>Channel gradient</td>
<td>0.0041</td>
</tr>
<tr>
<td>Max. riverbed width [m]</td>
<td>67.0</td>
</tr>
<tr>
<td>Max. stream depth [m]</td>
<td>2.3</td>
</tr>
<tr>
<td>Mean/Max. annual discharge [m³s⁻¹]</td>
<td>12.7/242.0</td>
</tr>
<tr>
<td>The 1997 flood peak [m³ s⁻¹]</td>
<td>256.0</td>
</tr>
</tbody>
</table>

No catastrophic perturbations are known to have affected the stream under study during the time of investigation. The flow probability appearance (Table 2) in the Skawa River for partial basin closed in Zembrzyce (A = 654.5 km²) indicates that flow during summer 2003 was low (IMGW, 2003).
Fig. 1. Localization of the research area.

<table>
<thead>
<tr>
<th>$P$ [%]</th>
<th>0.01</th>
<th>0.1</th>
<th>0.2</th>
<th>0.5</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>40</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q$ [m$^3$/s]</td>
<td>1005</td>
<td>785</td>
<td>716</td>
<td>622</td>
<td>549</td>
<td>473</td>
<td>428</td>
<td>395</td>
<td>370</td>
<td>288</td>
<td>205</td>
<td>179</td>
<td>158</td>
<td>128</td>
<td>113</td>
</tr>
</tbody>
</table>

The basic parameters of the planned reservoir are listed in Table 3.

Table 3

Characteristics of the Świnna Poreba water reservoir

<table>
<thead>
<tr>
<th>Variables</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water reservoir area [ha]</td>
<td>1035</td>
</tr>
<tr>
<td>Max. water capacity [mln m$^3$]</td>
<td>161</td>
</tr>
<tr>
<td>Flood reservoir capacity [mln mln$^3$]</td>
<td>50</td>
</tr>
<tr>
<td>Max. reservoir water level [m a.s.l.]</td>
<td>312.00</td>
</tr>
<tr>
<td>Min. reservoir water level [m a.s.l.]</td>
<td>288.50</td>
</tr>
<tr>
<td>Normal reservoir water level [m a.s.l.]</td>
<td>309.60</td>
</tr>
</tbody>
</table>
2.2. Field measurements (techniques)

2.2.1. Survey measurements

The measurements near Zembrzyce were carried out in 31 cross-sections along a 1800-m long reach (Fig. 2). The cross-sections are located on the Skawa River in the Świnna Poręba water reservoir backwater reach between two tributary mouths: Paleczka and Tarnawka Streams. The width of water surface during measurements varied from 9 to 50 meters.

Fig. 2. The measurement area with indicated measured cross-sections.

The riverbed slope of the Skawa River in Zembrzyce varies from 1 to 7 %, with an average value of 4.1%, as shown in Fig. 3. Typical cross-sections of the Skawa River are presented in Fig. 4. In cross-section XIV-XIV where the upper mouth Paleczka is located, the measured slope of the water surface is 6.8%. The survey measurements were calibrated based on the actual geodesy maps with a scale of 1:10000.

The shape of the sediments found in gravel bars was determined using Wolman method (Radecki-Pawlik, 2000). The granulometry was measured using traditional sieve-curve method.
2.2.2. Bedload characteristics

Grain size distribution was measured by using two methods: collection and sieving of bed material from an area of 1 m$^2$ using the set of field meshes and in situ sample freezing method which allows collecting intact samples of bedload (Carling and Reader, 1981). Sieve curves were done for riverbed gravel bars. The measurement of the granulometry for several layers along the depth provides a better description and understanding of bed stability and degradation/aggradation processes. The bed of the Skawa River reflects the changes in flow dynamics. Fig. 5 shows an example of sieve curves gathered for the riverbed: $d_m = 0.078$ m, $\sigma = 3.2$. Table 4 shows the variations in granulometry for samples collected along a 1800m-long reach extending from Zembrzyce bridge to Paleczka river mouth. The measurements show that the armoring is more important in the river bed than near the river banks.
Fig. 5. Sieve curves for the sediment sample taken from riverbed, $d_m = 0.078$ m, $\delta = 3.2$, which was used in numerical simulations.

<table>
<thead>
<tr>
<th>Characteristic diameter</th>
<th>gravel bar 4</th>
<th>No 5 flow current (bar 4 region)</th>
<th>No 6 left bank (bar 4 region)</th>
<th>Bridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{16}$ [cm]</td>
<td>1.10</td>
<td>1.35</td>
<td>1.45</td>
<td>2.15</td>
</tr>
<tr>
<td>$D_{50}$ [cm]</td>
<td>4.90</td>
<td>6.45</td>
<td>4.20</td>
<td>6.70</td>
</tr>
<tr>
<td>$D_{55}$ [cm]</td>
<td>5.87</td>
<td>8.90</td>
<td>5.45</td>
<td>8.20</td>
</tr>
<tr>
<td>$D_{85}$ [cm]</td>
<td>9.97</td>
<td>11.70</td>
<td>8.50</td>
<td>12.90</td>
</tr>
<tr>
<td>$D_{90}$ [cm]</td>
<td>13.6</td>
<td>12.55</td>
<td>11.20</td>
<td>14.50</td>
</tr>
<tr>
<td>$d_m$ [cm]</td>
<td>7.69</td>
<td>4.98</td>
<td>6.55</td>
<td>9.29</td>
</tr>
<tr>
<td>$\delta$ [ - ]</td>
<td>3.01</td>
<td>2.94</td>
<td>2.42</td>
<td>2.45</td>
</tr>
</tbody>
</table>

$\delta$ – standard deviation of sieve curve

The characteristic grain diameters for the river reach under consideration

The shape characteristics were of 1055 grains, which are mostly flat (59% – ellipsoids, 38% – disks and rods, and 3% – spheres), were measured. The grain shape characterization using spherical coefficient $\Psi_p = [(b/a)^2*(c/a)]^{1/3}$ shows that grains responsible for bed stability are disks and lengthened boards. The finer grains are more spherical in shape (spheroids and ellipsoids) (see Table 5). The mean value of shape factor is $SF = 0.38$, which confirms the fact that the grains in the sector of the Skawa River under study are flat. Bed roughness for the research reach was in the range between 0.035 and 0.052.
Table 5
Grain shape composition of the bed-material [%]

<table>
<thead>
<tr>
<th>Grain shape</th>
<th>Grain size class [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt;8</td>
</tr>
<tr>
<td>Grain amount [%]</td>
<td></td>
</tr>
<tr>
<td>Spheroid</td>
<td>0.00</td>
</tr>
<tr>
<td>Flatten ellipsoid</td>
<td>0.00</td>
</tr>
<tr>
<td>Lengthened ellipsoid</td>
<td>0.00</td>
</tr>
<tr>
<td>Disk</td>
<td>11.11</td>
</tr>
<tr>
<td>Lengthened board</td>
<td>33.33</td>
</tr>
<tr>
<td>Cylinder</td>
<td>55.56</td>
</tr>
</tbody>
</table>

In the Skawa River the armored layer is built of flat grains which can be easily transported. The critical shear stresses vary for every fraction due to grain shape characterization as well as hiding, armoring and sorting processes. The incipient motion of every fraction can be better described by using nondimensional Shields’ curve not only for the mean diameter, \( d_{50} \), but also for the representative sizes of different size fractions.

The \textit{in situ} measurements for describing bedload transportation in Polish Carpathian rivers were done by Michalik (2000) and Bartnik (1997) who proposed calculating the \( f_m \) by the formula:

\[
f_m = 0.0123 \ e^{1.6 SF}.
\]

The use of above formula allows calculating \( f_1 \) and \( f_2 \) in Wang formula. For the Skawa River calculations, the Shields stresses having values of \( f_1 = 0.045 \) (for \( d_l/d_m < 0.6 \)) and \( f_2 = 0.03 \) (for \( d_l/d_m \geq 0.6 \)) were used.

2.3. Computer models

2.3.1. CCHE2D model

CCHE2D is a state-of-the-art two-dimensional, unsteady, turbulent river flow, sediment transport, and water quality evaluation model (Jia and Wang, 2001; Wu, 2001; Khan, 2003; and Duan et al., 2001). The model is targeted for applications in the areas related to prediction of the riverbed and bank erosion for both uniform and non-uniform sediments, meander migration, and water quality. The model is used for evaluating the effects of the hydraulic structures on both river morphology, and water quality for riverine habitats. The CCHE2D is capable of simulating the transition between subcritical and supercritical flow in or near hydraulic structures, sudden river
morphological changes such as channel expansion and contraction, and river mixing processes for water quality and pollutant transport. CCHE2D is a state-of-the-art sediment transport model for both uniform and non-uniform sediment transport under equilibrium or non-equilibrium conditions. In the present case, however, the prediction of sediment transport and fluvial processes in the Skawa River require development of special procedures that can take into account the modified critical shear stress due to the presence of flat gravels and the armouring of the bed.

The CCHE2D model solves depth-integrated shallow water equations for all hydraulic calculations (Jia and Wang, 2001). Because many open channel flows are shallow, the effect of vertical motion is usually negligible. The depth-integrated 2D horizontal equations are generally accepted to be suitable for studying open channel hydraulics with reasonable accuracy. In addition, free surface elevation for the flow is calculated by the depth-integrated continuity equation, which is widely accepted and utilized for 2D models. Also the CCHE2D model uses the Efficient Element Method (special finite element method) to discretize the 2D depth-averaged shallow water flow equations. The inertial terms in the momentum equations are discretized using convective shape functions (upwinding) to achieve stability. The other terms in the equation are discretized using modified Lagrangian interpolating functions. In order to avoid node to node oscillations in the numerical solution, the convective terms in the momentum equation need to be computed in a way that the flow information from the upstream is emphasized to a degree corresponding to the strength of the convection.

The stresses $\tau_{ij}$ in the momentum equations are approximated using the Boussinesq assumption with a coefficient of eddy viscosity $\nu_t$. The model provides three different turbulent closure schemes for evaluating turbulent viscosity $\nu_t$ in the momentum equations: depth-averaged model, mixing length eddy viscosity model and $k-\varepsilon$ turbulence closure scheme. In hydraulics there are numerous ways to evaluate the shear velocity at the channel bed. Two alternatives are adopted in the CCHE2D model. The first is using the depth-integrated logarithmic law; the second is using Manning's coefficient. For practical applications the second method is recommended because it is easier to lump the effects of bed form, channel geometry, sediment size and vegetation, etc. into this coefficient. But for detailed near-field simulation/verification with experimental data, the first approach is physically sound and thus is worth adopting if roughness parameter is available.

The bedload transport formula developed by van Rijn is adopted, where the critical shear stress is calculated according to Yalin's suggestion, which modified the Shields curve.

The shear stress $\tau$ in this formula is evaluated from

$$\tau = \gamma(u/C')^2,$$

(2)
where \( C' = 7.8 \ln \left( \frac{12h}{3d_w} \right) \).

The model takes into consideration the bedload motion affected by transversal slope and by the secondary flows. The critical shear stress obtained from flat bed assumptions has to be corrected according to the slope angles in the streamwise and transversal directions. Furthermore, natural river channels usually have curved meandering patterns. When water flows along a curved channel with varying radius of curvature, secondary currents are generated due to the centrifugal force; bed load always tends to move towards the inner bank of the channel; which systematically makes the channel more and more curved.

The calculation of bedload transport for mountain rivers can be performed using SEDTRA module in which 3 bedload equations are implemented:

- \( 0.01 - 0.15 \) mm – Laursen,
- \( 0.15 - 2.0 \) mm – Yang,
- \( >2.0 \) mm – Meyer-Peter and Muller (MPM).

2.3.2. Mesh generator

The first step to start simulations is creating a mesh. The mesh is generated based on the surveyed topography. There are several methods to interpolate the interior nodes in the mesh, and later, to smooth the already created mesh. The equations used for smoothing mesh include Poisson equation, variational Laplace equations and Laplacian method (Zhang and Jia, 2002). Once an appropriate mesh is generated, the elevation values are assigned to the nodes to create topography of the research area.

Fig. 6. A portion of the mesh used for numerical simulations.
In Fig. 6 the mesh generated for the chosen section of the Skawa River research reach is presented. The cells representing the riverbed are concentrated in the middle part of the mesh.

3. Results

3.1. Shear stresses and water levels

Using CCHE2D model, simulations were carried out for the water discharges $Q = 35, 112$ and $205 \text{ m}^3\text{s}^{-1}$ and for the reservoir water levels 304.56, 306.50, 307.80 and 309.60 m a.s.l. Figure 7 presents water surface for discharges $Q = 35, 112$ and $205 \text{ m}^3\text{s}^{-1}$ for a reservoir water level at 304.56 m a.s.l. The average slope of water level for discharge $Q = 112 \text{ m}^3\text{s}^{-1}$ is equal to $3.5\%$ and for $Q = 205 \text{ m}^3\text{s}^{-1}$ is $3.7\%$, respectively. It can be predicted that for discharges greater than maximum simulated discharge the slope of the water surface in the river will tend to the overall bed slope of the Skawa River valley, which is about $4.1\%$.

![Fig. 7. Simulated water surface levels (WSL) for a reservoir water level at 304.56 m a.s.l.](image)

Figure 8 shows the water-surface profiles computed for a flow discharge of $Q = 35 \text{ m}^3\text{s}^{-1}$ and different reservoir water levels. For these flow conditions the backwater region is rather short. Depending on the reservoir water level, the backwater reach length varies from a few hundred meters to about 1.5 km. For still higher flow rates the length of the reach affected by the backwater is even longer.

Water surface levels (WSL) computed with CCHE2D are presented in Fig. 9. The simulations were run for discharges $Q = 35, 112, 205$ and $280 \text{ m}^3\text{s}^{-1}$ and the normal reservoir water level equal to 309.60 m a.s.l. At this WSL, the selected cross-section XIV-XIV is located within back-water of the Świnna Poręba reservoir. Also, the back-water region for bankfull discharge is about 0.5 km.
Fig. 8. Simulated water-surface profiles for a discharge of $Q = 35 \, m^3 \cdot s^{-1}$ and different reservoir water levels.

Fig. 9. Calculated WSL for different discharges and the reservoir water level 309.60 m a.s.l.

The incipient motion criterion for bedload transport is often based on the critical shear stress. Table 6 presents calculated critical shear stresses $\tau_c$ and shear stresses $\tau_o$ for different discharges and different water surface levels in the reservoir. At the selected region – along the cross-section XIV-XIV – shear stresses were obtained from simulations with CCHE2D. For instance, runs D01-D04 are performed for a discharge of 205 $m^3 \cdot s^{-1}$ and the reservoir water levels were set up as 304.56, 306.50, 307.80, 309.60 m a.s.l. respectively.
<table>
<thead>
<tr>
<th>Run</th>
<th>Critical shear stress $\tau_{cr}$ [N·m$^{-2}$]</th>
<th>Shear stress at the sampling point for the XIV-XIV cross-section $\tau_0$ [N·m$^{-2}$]</th>
<th>Max $\tau$ within XIV-XIV cross-section $\tau_{max}$ [N·m$^{-2}$]</th>
<th>Water discharge $Q$ [m$^3$·s$^{-1}$]</th>
<th>WSL [m a.s.l.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>D01</td>
<td>57.63</td>
<td>98.27</td>
<td>205</td>
<td>304.56</td>
<td></td>
</tr>
<tr>
<td>D02</td>
<td>59.47</td>
<td>70.85</td>
<td>206</td>
<td>306.50</td>
<td></td>
</tr>
<tr>
<td>D03</td>
<td>57.60</td>
<td>68.83</td>
<td>112</td>
<td>307.80</td>
<td></td>
</tr>
<tr>
<td>D04</td>
<td>9.45</td>
<td>20.79</td>
<td>309.60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D09</td>
<td>44.59</td>
<td>49.20</td>
<td>112</td>
<td>304.56</td>
<td></td>
</tr>
<tr>
<td>D10</td>
<td>37.35</td>
<td>41.07</td>
<td>306.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D11</td>
<td>37.18</td>
<td>41.34</td>
<td>307.80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D12</td>
<td>0.52</td>
<td>16.38</td>
<td>309.60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D17</td>
<td>17.19</td>
<td>17.51</td>
<td>304.56</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D18</td>
<td>17.18</td>
<td>18.28</td>
<td>306.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D19</td>
<td>12.21</td>
<td>13.96</td>
<td>307.80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D20</td>
<td>0.81</td>
<td>1.87</td>
<td>309.60</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The reservoir water level strongly influences the incipient motion of sediment at the selected cross-section. Calculations using ARMOUR software along cross-section XIV-XIV show that critical shear stress for the armored bed is equal to 70 N·m$^{-2}$ (Bartnik et al., 2004). This value is exceeded in some reaches only when the flow discharge is $Q = 205$ m$^3$·s$^{-1}$ and the reservoir water surface elevation is less than the normal reservoir elevation (309.60 m a.s.l.). For other flow situations the incipient values for the initiation of bedload transport are not exceeded.

The deposition takes place when $\tau_0 < \tau_{cr}$. For normal reservoir water elevation, one can expect a strong deposition at the selected cross-section for discharges $Q = 205$ and $112$ m$^3$·s$^{-1}$ (there is no sediment transport for the discharge $Q = 35$ m$^3$·s$^{-1}$). For reservoir water surface lower than the normal one and $Q = 112$ m$^3$·s$^{-1}$, the individual grains larger than the mean diameter start settling at the selected cross-section. For $Q = 205$ m$^3$·s$^{-1}$ armour layer starts to form. When the reservoir water level falls down to 304.56 m a.s.l. or lower, the deposition zone move downstream.

One can expect strong deposition at the back-water reach of reservoir. On the other hand water surface fluctuations due to the operation of the reservoir will also have an influence where the deposition takes place. This problem, however, could be the subject of another research project.
3.2. Bedload transport calculations using CCHE2D model

The CCHE2D model has been validated using a variety of test cases involving: laboratory flumes and natural rivers, channels with and without hydraulic structures, sediment transport, aggradation and degradation of the movable bed, flow domain with multiple inlets and outlets, flow in river bends, etc. For bedload transport calculations three methods can be chosen depending on river characterization. The formulas allow calculating bedload transport in lowland and mountain rivers as well. Roughness of bed material can be calculated using Wu and Wang or SEDTRA module (Wu, 2001).

The modelling process can be divided into two parts. The first part is the flow stabilization/calibration part. Later, when the steady flow initial conditions are reached, the bedload transport simulation starts.

The preliminary results of bedload transport calculations on the upper part of the research section of the Skawa River

In order to get acquainted with the modelling of bedload transport using CCHE2D, first a preliminary mesh was constructed covering only the upper part of the research reach.

The results of simulations with the preliminary mesh are presented in Fig. 10 and in Table 7. Both 205 and 280 m$^3$/s can be regarded here as discharges which remove the armour layer and initiate the sediment-transport process. These preliminary simulations with CCHE2D revealed the existence of erosion and deposition zones at the upper part of the research section, even for the flow discharge of 205 m$^3$/s (Fig. 10).

![Fig. 10. Measured and simulated bed elevations for a section of the Skawa River.](image-url)
Table 7
Hydraulic conditions of bedload transport at selected points along the research section of the Skawa River

<table>
<thead>
<tr>
<th>Description</th>
<th>Discharge $Q = 205$ m$^3$/s</th>
<th>Discharge $Q = 280$ m$^3$/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial bed elevation [m a.s.l]</td>
<td>315.09</td>
<td>315.14</td>
</tr>
<tr>
<td>Final bed elevation [m a.s.l]</td>
<td>315.09</td>
<td>315.07</td>
</tr>
<tr>
<td>Water surface level [m a.s.l]</td>
<td>317.07</td>
<td>316.85</td>
</tr>
<tr>
<td>Initial water depth [m]</td>
<td>1.98</td>
<td>1.71</td>
</tr>
<tr>
<td>Velocity magnitude [m s$^{-1}$]</td>
<td>2.19</td>
<td>2.41</td>
</tr>
<tr>
<td>Bed shear stress [N m$^{-2}$]</td>
<td>31.92</td>
<td>31.79</td>
</tr>
<tr>
<td>Bedload transport rate [kg s$^{-1}$m$^{-1}$]</td>
<td>0.61</td>
<td>1.52</td>
</tr>
</tbody>
</table>

For the flow discharge 205 m$^3$/s the CCHE2D model gives bedload transport rates ranging from 0.61 to 3.3 kg s$^{-1}$m$^{-1}$.

The whole research section bedload transport simulation

In the second phase of the study a new mesh covering the entire research reach of the Skawa River was prepared and bedload transport modeling simulations were carried out using CCHE2D.

Bedload transport simulations with CCHE2D were carried out using the equations of Wu and SEDTRA. Results of these simulations are presented below:

CCHE2D simulations revealed that the locations of erosion and deposition zones depend on the reservoir water level. The deposition takes place within backwater reach of water reservoir.

Both $Q = 205$ m$^3$.s$^{-1}$ and $Q = 280$ m$^3$.s$^{-1}$ flows can be treated as discharges which remove the armour layer and initiate the sediment transport processes. Measured and simulated bed levels for water discharges $Q = 205$ m$^3$.s$^{-1}$ and $Q = 280$ m$^3$.s$^{-1}$ are presented in Figs. 11 and 12, respectively. At these flow conditions the backwater region influences deposition zones. The deposition zones appear within backwater reach. Lowering reservoir water surface level for about 5 m displaces the deposition zone to a new location about 1.3 km downstream. For higher flow rates and different reservoir WSLs this distance will be longer. The results for $Q = 112$ m$^3$.s$^{-1}$ are not presented because the bed elevation changes for this discharge are very small and negligible.

Bedload transport causes changes in bed material properties. Figure 13 presents initial and final median sizes, $d_{50}$, at a section of the Skawa River for discharges
Fig. 11. Measured and simulated bed elevations for a section of the Skawa River for WSL 304.56 m a.s.l.

Fig. 12. Measured and simulated bed elevations for a section of the Skawa River for normal WSL.
Fig. 13. Initial and final median size $d_{50}$ for a section of the Skawa River for normal WSL.

$Q = 205 \text{ m}^3\text{s}^{-1}$, $Q = 280 \text{ m}^3\text{s}^{-1}$ and $Q = 112 \text{ m}^3\text{s}^{-1}$ with the normal reservoir water surface level. The initial and final median sizes, $d_{50}$, for the discharge $Q = 112 \text{ m}^3\text{s}^{-1}$ are not very different because the discharge is not high enough to entrain bed material. The median size $d_{50}$ for the discharge $Q = 205 \text{ m}^3\text{s}^{-1}$ increases where erosion takes place, i.e., at the beginning of the section of the Skawa River. This is the result of the wash away of the small size fractions in the bed material. This process is rendered visible by the increase of the median size $d_{50}$ from about 0.06 m to about 0.1 m. Entrained into motion, the bed material is transported and deposited within backwater reach of the reservoir. In this case median size $d_{50}$ decrease to about 0.04 m and finally reaches the initial size.

It seems that the flow rate $Q = 280 \text{ m}^3\text{s}^{-1}$ causes intensive bedload transport. All sediment fractions are transported as a bedload layer and the changes in bed material characteristics are very small.

At the beginning of section of the Skawa River the erosion takes place. When finer fractions are washed away from the bed material, the percentage of coarser fractions increases. This results in the formation of an armour layer. The bed material composition for the size class $d > 0.08$ m (size class 5) is plotted in Fig. 14 for a section of the Skawa River under normal WSL conditions. The initial bed material composition for size class $d > 0.08$ equals 40.6%. For the simulation with $Q = 205 \text{ m}^3\text{s}^{-1}$, at the beginning of the section of the Skawa River the amount of size class 5 increases to about 70-80%. Formation of the armour layer is observed along a distance of about
Fig. 14. Bed material composition for size class $d > 0.08$ m for a section of the Skawa River for normal WSL.

400 m. When the deposition takes place, the bed material composition for size class $d > 0.08$ decreases to 20% and finally becomes similar to the initial composition.

Measured and simulated grain size distributions at cross-section III-III are presented in Fig. 15. Final grain size distribution contains less fine fractions in comparison to the initial one. Water flow washes away small grains, transports them downstream and deposits them within back water reach.

Figure 16 presents measured and simulated grain size distributions at cross-section XIV-XIV for the discharge $Q = 280$ m$^3$s$^{-1}$ and the reservoir water level 309.60 m a.s.l. Final grain size distribution contains less coarse and more fine material in comparison with the initial one. This is due to the changes caused by deposition of bed material transported during flood.

A total bedload transport rate for selected cross-sections I, III, IV, X, XIV and XXVI of research reach of the Skawa River for reservoir WSL 304.56 m a.s.l. and normal WSL 309.60 m a.s.l. is presented in Figs. 17 and 18, respectively. The total bedload transport rate is obtained by summing bedload transport in nodes along the selected cross-sections. Figure 17 presents the influence of the water reservoir surface level on the reduced value of bedload transport rate.
Fig. 15. Grain size distribution at cross-section III-III for discharge $Q = 205 \, \text{m}^3\text{s}^{-1}$.

Fig. 16. Grain size distribution at cross-section XIV-XIV for discharge $Q = 280 \, \text{m}^3\text{s}^{-1}$.

The amount of bedload material transported during simulated passage of flood was evaluated to be about 1100 m$^3$. This bed material will be deposited within backwater reach of the reservoir. The accumulated material will increase the river bed level. The reduction of active cross-section will cause the increase of water levels during a flood. The investigation of the deposition processes during exploitation of future reservoir must be studied beforehand in order to avoid flooding of the nearest village, Zembrzyce.
Fig. 17. Total bedload transport rate within selected cross-sections of a section of the Skawa River for reservoir WSL 304.56 m a.s.l.

Fig. 18. Total bedload transport rate for selected cross-sections of a section of the Skawa River for normal reservoir WSL.
3.3. Suspended load transport simulations

The initial composition of suspended load material is presented below.

<table>
<thead>
<tr>
<th>(d_i) [mm]</th>
<th>(p_i) [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001</td>
<td>0.08</td>
</tr>
<tr>
<td>0.010</td>
<td>0.12</td>
</tr>
<tr>
<td>0.034</td>
<td>0.3</td>
</tr>
<tr>
<td>0.040</td>
<td>0.2</td>
</tr>
<tr>
<td>0.048</td>
<td>0.2</td>
</tr>
<tr>
<td>0.079</td>
<td>0.1</td>
</tr>
</tbody>
</table>

In Fig. 19, the suspended load transport is stopped within back-water reach of reservoir. The reservoir accumulates huge amount of suspended load. In Fig. 18, suspended load concentration for the fraction 0.079 mm is shown for two simulations using the same discharge of \(Q = 205\ \text{m}^3\text{s}^{-1}\) but different reservoir water levels: 304.56 m a.s.l. and 309.60 m a.s.l. (normal reservoir WSL). For the case with 309.60 m a.s.l., the concentration for fraction 0.079 mm falls down to nearly zero in the back-water region of the reservoir.

![Graph of suspended load concentration](image)

Fig. 19. Suspended load concentration for the fraction 0.079 mm obtained from two simulations with discharge \(Q = 205\ \text{m}^3\text{s}^{-1}\) and reservoir water surface levels at 304.56 m a.s.l. and 309.60 m a.s.l.
4. An attempt to verify CCHE2D model

The ability of CCHE2D to predict bedload transport and armour layer formation was verified by comparing the simulation results with those obtained with TRANS (Bartnik, 1997) and ARMOUR (Bartnik and Strużyński, 1999), which are calibrated for Polish Carpathian rivers and streams.

Bed roughness

Bed roughness height was measured by the profile-meter AG-1 (Bartnik and Strużyński, 2002). The gauge is used to describe both uniform and nonuniform bed loads.

The use of standard deviation ($K$) of profile-meter telescope plummets’ distance from bed (eq. 3) allows describing roughness measure. Sand roughness found in log-law equation for uniform bed roughness, with defined shape factor, can be obtained using the profile-meter by using equation (4)

$$K = \sqrt{\frac{1}{n-1} \sum_{n=1}^{N} (h_n - H)^2} ,$$  

where $N$ is the amount of profile-meter telescope plummets, $h_n$ is the $n^{th}$ plummet length, $H$ – the mean profile-meter distance from bed, and $K$ – the bed roughness measure.

$$k_s = K (1.926 SF^2 - 0.488 SF + 4.516)$$

where $SF$ is the shape factor of the grains.

<table>
<thead>
<tr>
<th>$K$ mean value</th>
<th>$K$ minimum</th>
<th>$K$ maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0235 m</td>
<td>0.0095 m</td>
<td>0.0384 m</td>
</tr>
</tbody>
</table>

Shape factor

The shape factor for gravels was measured using linear method.

<table>
<thead>
<tr>
<th>$SF$ mean value</th>
<th>$SF$ minimum</th>
<th>$SF$ maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.38</td>
<td>0.14</td>
<td>0.77</td>
</tr>
</tbody>
</table>

The shape factor of the bed material influences the value of critical shear stress for the initiation of motion.
TRANS and Armour softwares

Bed load transport was calculated using the TRANS software in which Meyer-Peter and Müller (M-PM with $k_s/k_r = 1$ and $Q_d/Q = 1$) method with Bartnik's modified calculation procedure (Bartnik, 1997) implemented. To improve the accuracy of bed-load transport calculations, the bed-load rates for different fractions were calculated separately.

The formation of an armour layer was modeled using the ARMOUR software (Bartnik and Strużyński, 1999), which is specially calibrated for Polish Carpathian rivers and streams. This modeling procedure is based on Gessler's analysis of the probability of grain movement on the basis of the shear stresses exerted by the flowing water (Sentürk, 1977). The critical shear stresses are calculated using the function developed by Wang (1970) for Carpathian streams. The armour layer is formed by the fraction of non-cohesive bed material that is not washed away during the flow.

The total bed-load transport rate is shown in Fig. 19 as a function of the water depth. Due to the particular composition of the bed material in the Skawa River, a substantial increase in the transported sediment mass is observed after a certain stage. The armoured layer takes part in the sediment-transport process only after the water depth exceeds 1.2 m (Fig. 20).

The noticeable increase in bedload transport rate appears after the water level reaches a depth of 2.5 m, and one can expect the bed armored level diminishes under the stage. Using TRANS software the amount of bedload transport was calculated as 2.3 kg s$^{-1}$ m$^{-1}$.

![Bedload transport rate graph](image)

Fig. 20. The bedload transport rate in the Skawa above the Paleczka Stream mouth (cross-section XIV).
Simulation of bed stability using ARMOUR

The formation of an armored layer was modeled using the ARMOUR software (Bartnik and Strużyński, 1999) calibrated for Polish Carpathian rivers and streams. This modeling procedure is based on the Gessler’s analysis of the probability of grain movement on the basis of the shear stresses of the acting water (Sentürk, 1977). The critical shear stresses are calculated using the Wang (1970) function developed for Carpathian streams. The armoring layer is formed by that part of non-cohesive bed material, which is not washed away during the flow.

The numerical simulations were carried out based on in situ and laboratory measurements made during 2003/2004, which had indicated very high bed stability. The armored layer remains stable as long as the water level is below 2.5 meters. When the water depth reaches 2.75 (Q10%) the armour layer is destroyed, and this causes massive transportation of bed material (Fig. 21). Under these flow conditions the critical shear stress reaches 70 [N·m²]. The simulation results can also be used to visualize the root causes of sorting and armoring processes (Fig. 22). Starting from the initial conditions, parameter δ decreases until the water level reaches 1.8 m (Q50%). During this period the small fractions are flushed from the bed surface and the sorting and armoring processes are occurring. For water stages from 1.8 m to 2.5 m, the τc slightly increases whereas δ stays approximately at the same value. When the water depth becomes higher than 2.5 m, the mixing process appears and the total bed-load transport starts.

The predictions performed with ARMOUR software (which is calibrated for the Skawa River flow conditions) for the modification of bed load granulometry after

![Graph showing granulometry change during the flood passage.](image)

**Fig. 21.** The simulation of granulometry change during the flood passage.
Fig. 22. Simulated parameters describing the hydraulic balance during armoring processes on the Skawa River.

the passage of the flood confirm the results obtained with the CCHE2D model (compare Fig. 15 and Fig. 21). This indicates that the hiding and sorting processes implemented in CCHE2D are appropriate to be used for simulating the fluvial processes in the Skawa River, and probably other Carpathian rivers.

5. Conclusions

The CCHE2D model was used to model the fluvial processes in the Skawa River reach within the zone of influence of back-water caused by the Świnna Poręba reservoir. The simulations were made under natural conditions where:

- the grain shape analysis shows that most grains discovered in the Skawa River reach i.e., 59% of them, are flat; there are 38% disks and rods, and only 3% spheres. The fine grains (d16) are mostly spherical in shape (spheroids and ellipsoids) but they do not contribute seriously to the stability of the riverbed. The mean shape factor for the Skawa River near Zembrzyce is 0.38,

- average slope of water level for discharges greater than those simulated tends towards the bed slope of the entire Skawa River valley, i.e. 4.1%,
the bankfull discharge equals 205 m³s⁻¹.

The parameters needed to calibrate the model were obtained from measurements using radioactive tracers to determine the critical condition of incipient motion:

- the results of simulations with CCHE2D model were verified based on the measurements and using DWE software, ARMOUR and TRANS. The advantage of using the CCHE2D model is that one can simulate morphological changes in two dimensions whereas ARMOUR and TRANS allow prediction of the parameters only at one selected cross-section,

- the armoured level consists of mostly flat grains, which are more easily entrained when flood occurs,

- the incipient motion of bed material is similar to other Carpathian rivers and streams, however the Shields factor for the Skawa River is characterized by slightly lower values $f_{m1} = 0.045$ and $f_{m2} = 0.030$,

- the removal of the armour layer and the total transport for the investigated Skawa reach starts when the flow discharge exceeds $Q_{20\%} = 205$ m³s⁻¹, which corresponds to a water depth of 2.30 m. The critical shear stresses reach 70 N m⁻².

Based on the results obtained from the simulations carried out with CCHE2D model, the following final conclusions and remarks can be proposed:

1. Field measurements which only included geodetic survey, granulometry analysis of bedload and hydrological calculations for the research cross-section are sufficient to generate a mesh and run CCHE2D model.

2. Calculated critical shear stresses along cross-section XIV-XIV for the armoured bed is equal to 70 N m⁻². This value is only exceeded for discharge $Q = 205$ m³s⁻¹ and reservoir WSL below the normal level (309.60 m a.s.l.).

3. Back-water created by the reservoir reduces the shear stress and influences the conditions for the initiation of bedload transport.

4. For normal reservoir water surface, substantial deposition takes place at selected cross-section. For reservoir water surface levels lower than the normal level, the individual grains larger than the mean diameter start settling when $Q = 112$ m³s⁻¹ and the formation of armour layer takes place when $Q = 205$ m³s⁻¹. When the reservoir water level falls down to 304.56 m a.s.l. or lower, the deposition zone moves downstream.

5. The differences in sediment transport using different models (ARMOUR and CCHE2D) are due to differences in the formulas used within the models for calculating sediment transport. In case of TRANS model, the shape factor of
grains is taken into account, that is probably why the transport calculated using this model is smaller than using CCHE2D, respectively 2.3 kg s\(^{-1}\)m\(^{-1}\) and 3.3 kg s\(^{-1}\)m\(^{-1}\).

6. Based on the simulations with CCHE2D with different reservoir levels and discharges, one can observe that the influence of back water of the reservoir may extend up to a distance about 1.3 km upstream. The location of deposition of bed material can be changed by controlling the reservoir water surface level.

7. The accuracy of simulations can be greatly improved by preparing a high quality mesh which covers research area and takes into consideration dimension, shape and orientation of individual cells.

8. Based on the results of simulations with CCHE2D, it was possible to localize regions where erosion and deposition take place. Those processes occur when the bed material is washed away at the upstream is transported downstream to settle within back-water reach of reservoir. These fluvial processes were successfully simulated with CCHE2D model.

9. The amount of bedload material transported during simulated passage of flood was evaluated to be about 1100 m\(^3\). This bed material is deposited within back-water reach of the reservoir.

10. The results of simulations with CCHE2D, which uses Wu et al. (2000) formula for calculating bedload rate, compare well with those obtained using ARMOUR/TRANS software, which are especially calibrated for Polish Carpathian rivers and streams. This leads to the conclusion that CCHE2D is appropriate for modeling bedload processes in the Skawa River.

The CCHE2D model is a useful tool in computational fluid dynamics. The model reproduces satisfactorily the morphological changes in the Skawa River caused by the back-water of Świnna Poręba dam. In the future, the model will be an important tool in establishing the operational rules for the exploitation of the Świnna Poręba reservoir.

**Acknowledgements.**

This work is a result of research sponsored by the US State Department Agency for International Development (US–AID) under Agreement No. EE-G-00-02-00015-00 and the University of Mississippi, which was technically supported by National Center for Computational Hydroscience and Engineering (NCHE).

The Agricultural University of Kraków carried out the project USPTTP02, in cooperation with NCCHIE at the University of Mississippi, within the framework of the program US-Poland Technology Transfer Program.
The authors would like to thank DWE MSc students for their help in field measurements: Paweł Baran, Jarosław Bencal, Dominik Chrustek, Anna Englert, Maciej Englert, Marcin Kowalski, Maciej Potaczek. Laboratory experiments were done under supervision of Alicja Michalik from DWE and MSc students Grzegorz Patalita, Jacek Piskorski.

References


CONTENTS

Foreword – Sam S.Y. Wang ................................................................. 3

Preface – Sam S.Y. Wang ................................................................. 5

Acknowledgements – W. Czernuszenko and P.M. Rowiński ..................... 7

Opening Addresses During the Closing Workshop September 30 – October 2, 2004, Mądralin Conference Center, Warsaw, Poland ................................................................. 9

M.A. Latif .................................................................................. 11

M.J. Gromiec ............................................................................ 13

W. Majewski ............................................................................ 15

P.M. Rowiński ........................................................................ 17

M.S. Altinakar ........................................................................ 19

Funded Research Projects .................................................................. 25

Recognition of Hydrological Processes in the Upper Narew Multichannel River System and Their Influence on Region Sustainable Development – P.M. Rowiński, J.J. Napiórkowski and M. Osuch ................................................................. 27

Forecasting of Fluvial Processes on the Skawa River Within Back-Water Reach of the Świnna Poręba Water Reservoir – W. Bartnik, K. Banasik, L. Książek, A. Radecki-Pawlik and A. Strużyński ......................... 57


Application of the CCHE1D Model to the Problem of Flood Control in Nysa Kłodzka Reservoir System in Poland – T. Dysarz, R. Szymkiewicz and K. Weinerowska ................................................................. 115

The Influence of River Training on Hydrodynamics and Morphological Changes in Open Channel Flow on the Example of the Lower Vistula River – M. Robakiewicz and Ł. Sobczak ................................................................. 149

Sediment Problems of Small River Catchments and Reservoirs in Poland – K. Banasik, L. Hejduk and Z. Popek ........................................................................ 179

Recognition of Hydraulic Conditions in the Upper Narew River System and Their Influence on the Wetland Habitats in the River Valley – J. Kubrak, T. Okruszko, D. Miroslaw-Świątek and I. Kardel ................................................................. 209

Immobilising of Sediments in a Lowland River Floodplain – A. Magnuszewski, E. Kiedrzyńska, J. Wagner-Łotkowska and M. Zalewski .......... 239