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Modelling of inundation patterns on the Pilica River flood plain, Poland

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Abstract Eutrophication of inland waters can be significantly prevented by enhancing the natural self-purification ability of rivers through deposition of their sediment load on the flood plain. One of the efficient ways to achieve natural sedimentation on the flood plain is through modification of natural vegetation cover by introducing willow plantations. Planning and implementation of such plantations require a sound understanding of the flow and sediment transport dynamics. In the present study, CCHE2D, a two-dimensional numerical hydrodynamic model developed at the National Center for Computational Hydroscience and Engineering (NCCHE) of the University of Mississippi, was used to investigate the flow pattern and sedimentation processes on a flood plain of the Pilica River, with and without plantations.

Key words Pilica River; flood plain sedimentation; river hydraulic modelling

INTRODUCTION

Suspended sediments transported by rivers are one of the main sources of phosphorus that controls the eutrophication process of inland and offshore waters. Several researchers have shown that, based on a sound understanding of natural ecosystems, the ecohydrology and biotechnologies can be used to prevent or reduce eutrophication of inland reservoirs and lakes (Zalewski, 2000; Zalewski, 2002; Wagner-Łotkowska *et al*., 2004; Kiedrzyńska *et al*., 2006). River self-purification by deposition of the sediment load in the channel and on the flood plains is one of the available mechanisms.

The water quality problems of the Pilica River are also related to the high concentrations of total phosphorous, which usually varies between 100 to 300 μg dm^{-3}, but can reach 699 μg dm^{-3} during high flows (Wagner-Łotkowska *et al.*, 2004). The Sulejów Reservoir, located downstream from the study area, is the main drinking water source for the Łódź conglomeration (over 1 million inhabitants) and also serves as a recreational area. The eutrophication of the reservoir during summer months (Tarczyńska *et al*., 2001) leads to high phytoplankton biomass productivity with cyano-bacteria domination. This is a very important problem for the entire region.

River flood plains play a crucial role in the exchange of water masses and matter between the river and terrestrial ecosystems and in the functioning of the river ecosystem (Junk *et al*., 1989). Sedimentation processes in river flood plains have been extensively discussed by several researchers (Nanson & Croke, 2002; Howard 1992; Tockner *et al*., 2000; Amoros & Bornette, 2002). Introduction of, for example, willow plantations to change the hydraulic resistance of the flood plain can be efficiently used to control the deposition rate of sediments on the flood plain and thus to enhance the retention of nutrients. However, many of the studies reviewed by Nanson & Croke (2002) have shown that the modification of the river flood plain vegetation cover may have broader consequences. It must, therefore, be studied carefully.

In the Pilica River case this problem is studied by predicting flow and velocity field patterns, as well as the sediment fluxes, with the help of a two-dimensional (2-D) numerical hydrodynamics and sediment transport model, called CCHE2D. Developed at the National Center for Computational Hydroscience and Engineering (NCCHE) of the University of Mississippi, CCHE2D is a depth integrated 2-D model for simulating free surface flows and sediment transport. It is based on depth-averaged Navier-Stokes equations, and is capable of bed load and/or suspended sediment transport simulations. The turbulent shear stresses are approximated using Boussineq's approximation and the turbulent eddy viscosity, with the use of three different closure schemes. The set of equations is solved implicitly using a control volume approach and efficient element method. The sediment flow is calculated assuming non-uniform material in a non-equilibrium transport model. The equations for suspended, bed load or total load are solved using the efficient element method or an exponential difference scheme. The model has been extensively verified and validated. It has been successfully applied to modelling complex flows in natural channels and is proven to constitute an efficient tool for hydraulic research and engineering projects (Jia *et al*., 2002). It can be efficiently used for simulating shallow water flow conditions on flood plains.

According to Lewin (2001) there is a relatively good understanding of fluvial processes at the discrete spatial scales of bed forms, channel processes and relief formation, but there is no single theory linking these various spatial scales. Sedimentation processes are acting across the scales, and they are controlled by factors such as the sediment-transport rate, channel relocation, reaction and relaxation time. An across-scales description of the fluvial processes is possible with the use of 2-D hydrodynamic models, which allow simulation of local flow parameters, as well as the general picture of the flow pattern and internal circulation. The complicated nature of flood plain flows during inundation by low probability floods is one of the principal rationales behind the use of numerical models, in spite of their limitations as discussed by Cao & Carling (2002).

DATA

Study site description

Located in central Poland, the Pilica River (Fig. 1) is a right-side tributary of the Vistula River. It has a length of 342 km and catchment area of 9258 km^2. It is mainly an agricultural catchment; forests comprise 30.7%, and other non agricultural land cover occupy 5.1%. Pilica River has a network of hydrological gauges operated by the Institute of Meteorology and Water Management (IMGW). Closest to the study site are the Sulejów gauge, located downstream (catchment area, A = 3909 km^2, river length, L = 161.3 km), and the Przedbórz gauge located upstream (A = 2536 km^2, L = 201.1 km). The study site is an experimental flood plain (26.6 ha) of the Pilica River valley located 4.5 km southwest of Sulejów town (Fig. 1).

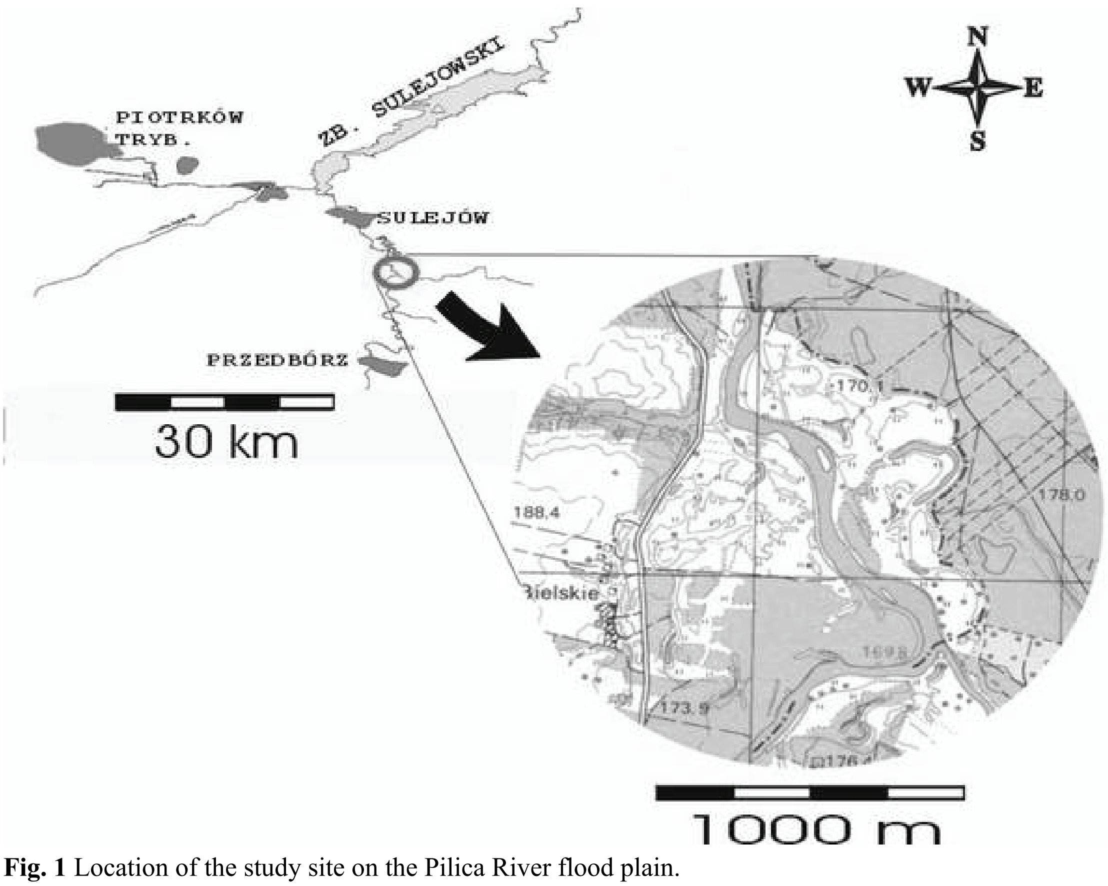

Fig. 1 Location of the study site on the Pilica River flood plain.

Suspended sediments concentrations were measured by IMGW at the Przedbórz gauge during the period 1957–1988. Concentration extremes vary from a minimum of 1 g m^{-3} to a maximum of 150 g m^{-3}. Average annual suspended sediment transport is 9500 t (data from the period 1957–1990), which corresponds to a denudation rate of 3.7 t km^{-2} (Brański & Banasik, 1996).

Nanson & Croke (1992) proposed classification of the flood plains formed in non-cohesive sediments into three classes: high, medium and low energy. According to this classification, the Pilica River flood plain at the study site belongs to the medium energy class, and is formed by a meandering channel. The Pilica River channel is not trained and has a free meandering pattern with natural sedimentation and erosion processes. The main channel near the study site is 20–60 m wide, with a large meander loop. Local depressions related to flood plain formation by meandering processes are visible in the flood plain relief.

The type of vegetation on the flood plain depends on the groundwater level and hydraulic conditions during flooding. Grasslands of the hay meadow type occupy the largest percentage of the flood plain surface. Sedge rushes grow on the plain to a lesser extent; the predominant species is the sharpened sedge, *Carex gracilis L.*, which occurs in small mid-meadow hollows, and to a lesser degree *Carex vesicaria L.* Rushes with common reeds (*Phragmites australis*, *Cav.*) Trin. Ex Stend. (common reeds), belonging to the habitat of rushes proper, grow in the old river bed of the Pilica River, in which water is retained throughout the year. For this reason also, the river valley and the researched flood plain have little agricultural value.

Data for the model

The CCHE2D hydraulic model requires the following input data to characterize the study site:

- elevation points which characterize the channel and flood plain form,
- Manning roughness coefficients representing various vegetation covers,
- boundary conditions of discharge at the inlet to the studied river reach,
- sediment properties and transport intensity.

A set of elevation points obtained from digitizing the contour lines on a topographic map supplemented by 815 levelling measurements were used to compute a Digital Elevation Model (DEM) using the inverse distance algorithm.

Using the field data from a botanical inventory and aerial photographs, a land-use map was produced containing five classes. The following Manning roughness coefficients were assigned to various parts of the flood plain: sand channel of Pilica, 0.025; oxbow channel, 0.070; grass, 0.035; reed; 0.050; willow, 0.150; forest, 0.100.

Hydrological data from the Sulejów gauge measured by IMGW was used for statistical analysis of water-stage frequency. GIS examination of the DEM gave the picture of flood plain inundation which starts at stage H = 210 cm (Q = 50 m^3 s^{-1}) reaching a maximum discharge at H = 300 cm (Q = 166 m^3 s^{-1}). Average duration of flood plain inundation in days was calculated by comparing the DEM with water levels and is represented graphically in Fig. 2.

The numerical grid of the model was generated using the Mesh Generator software developed at the NCCHE. A set of x,y,z coordinates were used as input to calculate the geometry of the river channel and flood plain for the CCHE2D model.

METHOD

The underlying concept of the project is the enhancement of sedimentation on the Pilica River flood plain by introducing plantations of willow trees to alter the vegetation cover. The four experimental plantations were introduced in the part of the flood plain under investigation (Fig. 2). The two largest are plantation No. 1 (900 m^2) and plantation No. 3 (1225 m^2). In the first approach the effect of the introduction of the plantations was studied by comparing the numerical results of natural conditions (Scenario 0), with those with the plantations (Scenario 1). The velocity fields were calculated for both scenarios assuming steady-flow conditions at water stages H = 210–300 cm with 10 cm intervals. Simulation time was 1000 s with the time step 1 s. The computed depth-averaged velocities in both scenarios were compared at two monitoring points located at the centres

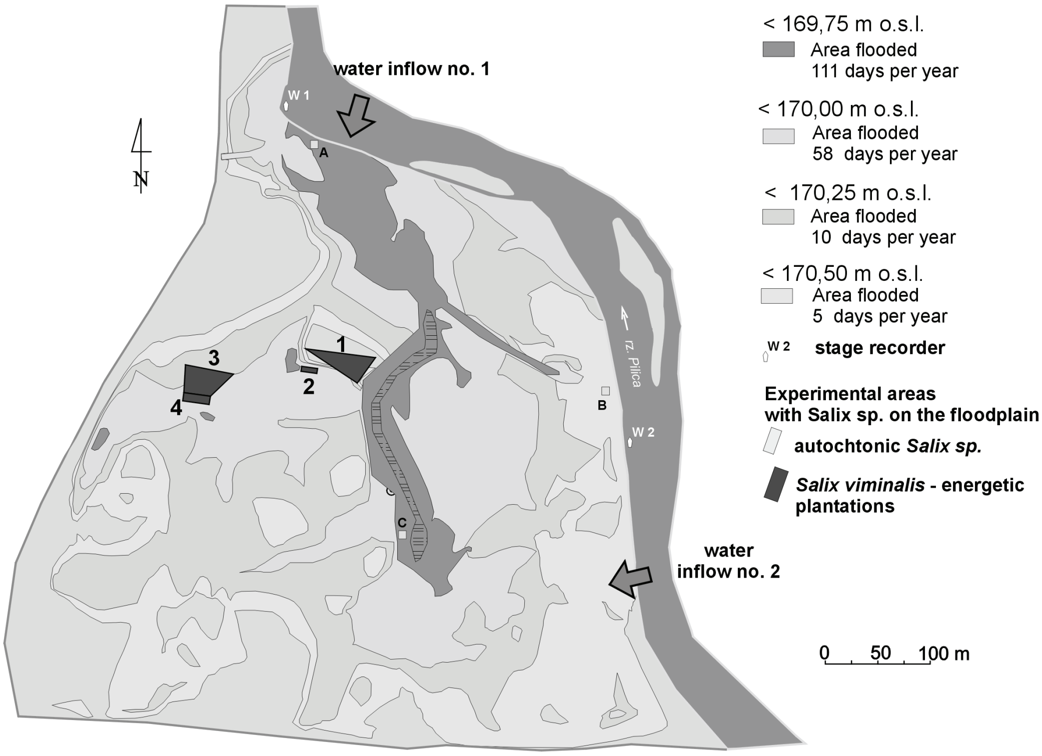

Fig. 2 Location of willows plantation and floodplain inundation duration in days.

of the largest plantations. Monitoring point MP1 is located at the centre of plantation No. 1, and monitoring point MP2 at the centre of plantation No. 3.

The relationship between suspended-sediment concentration and discharge was analysed using water stages from the Sulejów gauge and suspended-sediment concentrations from the Przedbórz gauge based on the observations recorded between 1984 and 1988. The relationship for the entire data set is very complex. The sediment supply is controlled by the snowmelt in the spring and vegetation cover in the summer. The best relationship between suspended sediment-concentration and discharge has been obtained for the period of late autumn, when sediment supply from the catchment to the river channel is not constrained. Generally, it is difficult to assign a single suspended-sediment concentration value to a given water stage or discharge.

In the period 1996–2003 suspended sediment-concentration measurements of the Pilica River at Sulejów profile were also made by the Department of Applied Ecology of Łódź University (Wagner-Łotkowska *et al.*, 2002). Detailed analysis of daily values of suspended sediment concentrations and discharges show a hysteresis effect, with the highest concentrations recorded earlier than peak flow. For example, during the small magnitude flood of 16–30 March 1996, which occurred after a longer period of low flows, the maximum suspended sediment concentration of 22 g m^{-3} was observed four days before the peak flow. The second flood wave 06–15 April 1996, with a similar peak discharge, caused sediment concentrations of only 4–9 g m^{-3}. This sequence of flows can cause a flushing effect on the sediments accumulated at the channel bottom. During moderate magnitude peak flows, we can expect the highest suspended sediment concentrations to be in the range of 20 g m^{-3}.

Samples of the suspended sediments from the Pilica River were collected using the PIHM bottle sampler, and processed by laser particle-size measurement. It was decided that in the numerical model a single diameter of suspended sediment, $d_{50} = 2.00 \times 10^{-5}$ m, will be used as the representative size.

The properties of the material deposited on the flood plain have been estimated from the samples collected in the field covering various sedimentation environments, such as the river channel, banks and oxbow lake deposits. The sample were analysed using a sieve-analysis method. River channel deposits are coarse, $d_{50} = 2.05–3.68 \times 10^{-4}$ m, and well graded. Bank deposits have a median diameter of $d_{50} = 1.37–1.97 \times 10^{-4}$ m and also show rather good grading. Sediments in the wetlands on the floodplain have median grain diameter, $d_{50} = 1.08–1.76 \times 10^{-4}$ m are poorly graded, with a high proportion of fine fractions (more details are given in Magnuszewski *et al*., 2005).

The sedimentological properties of the Pilica River bed load and suspended sediments at the study site are distinctly different. Bed load material is transported in the river channel where the water energy is adequate. The analysis of soil samples indicates that the material deposited on the flood plain has a smaller diameter than river channel sediments. The suspended sediment transport and deposition play a more significant role in forming the flood plain surface than the bed load transport of coarse sediments. Therefore, it was decided that the simulation of the sedimentation processes at the Pilica River flood plain study site will be done taking into account only suspended sediment transport.

RESULTS

Influence of willow plantations on water and sediments fluxes

The results of the calculations are given in Table 1. Plantation No. 1 is situated on a higher terrace, and is inundated only at stages H = 280 cm (Q = 133 $m^3 s^{-1}$) and higher. This elevation is flooded only during major floods. Plantation No. 3 is located at an elevation which flooded on average 10 days per year. Comparisons of the numerical simulation results for two scenarios, natural conditions (Scenario 0) and land cover altered by willow plantations (Scenario 1) shows that changing the roughness of even a relatively small area considerably reduces the velocity field. Willow plantations are found to be particularly useful in creating dense and compact vegetation cover with high Manning coefficients values.

Table 1 Results of the velocity calculations at the monitoring points according to scenario 0 – natural conditions, and scenario 1 – implementation of the plantation scheme; *H* is water stage, *Q* is discharge, and v_h is average velocity.

H (cm)	*Q* ($m^3 s^{-1}$)	MP1: Scenario 0 v_h ($m s^{-1}$)	Scenario 1 v_h ($m s^{-1}$)	MP2: Scenario 0 v_h ($m s^{-1}$)	Scenario 1 v_h ($m s^{-1}$)
210	50.0	0	0	0	0
220	59.0	0	0	0	0
230	68.0	0	0	0.00308	0.00135
240	79.0	0	0	0.00173	0.00215
250	90.0	0	0	0.00521	0.00496
260	102	0	0	0.0121	0.00910
270	117	0	0	0.0181	0.0152
280	133	0.247	0.0670	0.0397	0.0256
290	149	0.291	0.0667	0.0577	0.0255
300	166	0.328	0.0852	0.0687	0.0384

The influence of willow plantations on the sediment trapping ability of the floodplain was analysed for flood simulation with H = 300 cm, using the same monitoring points located at the centre of larger plantations, No. 1 and 3. Suspended sediment concentration corresponding to Q = 166 $m^3 s^{-1}$ has been calculated as $C_s = 0.035$ kg m^{-3}. For this run, the simulation duration for the suspended sediments transport was increased to 10 000 s. The results obtained (Table 2) give an idea of the spatial distribution of suspended sediment transport (Fig. 3), and provide a good indication of the potential sedimentation zones at the study site. Both willow plantations, No. 1 and No. 3, are located at the edge of high sediment transport and sedimentation areas. This location is a compromise between moderate sedimentation potential, proper moisture conditions at the willows root zone, and the availability of space for performing the experiments (land ownership).

The sediment-transport pattern calculated by the CCHE2D model has shown that suspended-sediment concentration decreases with distance from the main channel, but exhibits a plume-like behaviour along major flow paths. This is in accordance with the findings of Nicholas (2003), who suggests that suspended-sediment transport on the natural flood plains is dominated by advection.

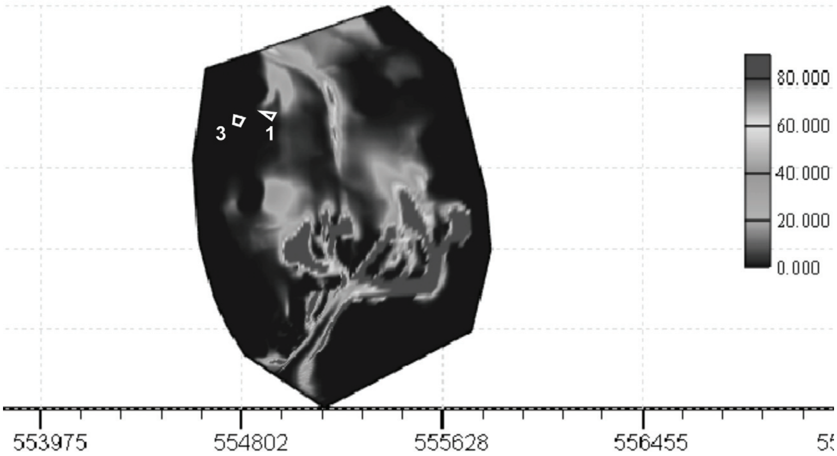

Fig. 3 Results of the suspended sediment transport simulation with willow plantations No. 1 and No. 3. Water stage $H = 300$ cm, $Q = 166$ m^3 s^{-1}, $Cs = 0.035$ kg m^{-3}, simulation time 10 000 s, time step 0.1 s.

Table 2 Results of the simulations at $H = 300$ cm flood with the suspended sediments transport for two selected monitoring points according to Scenario 0 – natural conditions, and Scenario 1 – implementation of the plantation scheme.

Hydraulic parameters from NCCHE2D model simulations at flood stage $H = 300$ cm	MP1 at plantation No. 1 $z = 170.4$ m a.s.l. Scenario 0	Scenario 1	MP2 at plantation No. 3 $z = 169.9$ m a.s.l. Scenario 0	Scenario 1
Sediment transport (kg s^{-1} m^{-1})	7.83	2.52	0.000255	0.000559
Elevation change (m)	–0.076	0.095	–0.00001	0.00001
Average velocity (m s^{-1})	0.236	0.185	0.0578	0.0472
Bed shear (N m^{-2})	1.24	0.835	0.0541	0.0376
Water column depth (m)	0.358	0.272	0.916	0.810
Specific discharge (m^2 s^{-1})	0.0846	0.0505	0.0530	0.0382

CONCLUSIONS

(a) Hydrodynamic model CCHE2D has been used successfully to simulate the water flow of the Pilica River for the case of flood plain inundation. The sediment-transport module of the model proved to be a very useful tool for studying fluvial processes, and self-purification of natural river channels.

(b) The location of willow plantations should be selected by considering various factors such as the risk of extreme flooding and the related bed deformations, damage due to high water velocities, and also the ice flow in spring time.

(c) Sequences of calculations at different water stages have shown the complex pattern of flood plain inundation and location of topographic lowering where water from the river channel cross the banks.

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