Modelling lowland reservoir sedimentation conditions and the potential environmental consequences of dam removal: Wloclawek Reservoir, Vistula River, Poland

ARTUR MAGNUSZEWSKI[1]**, SHARON MORAN**[2] **& GUOLIANG YU**[3]

1 *University of Warsaw, Faculty of Geography and Regional Studies, Department of Hydrology, Krakowskie Przedmiescie 30, 00-927 Warszawa, Poland*
asmagnus@uw.edu.pl

2 *State University of New York, Department of Environmental Studies, 107 Marshall Hall, 1 Forestry Drive , Syracuse, New York 13210-2787, USA*

3 *Shanghai Jiao Tong University, Department of Harbor, Waterway and Coastal Engineering, School of Naval Architecture, Ocean and Civil Engineering Shanghai, Dongchuan Road 800, Shanghai 200240, China*

Abstract The decommissioning of dams has been discussed on an international scale in the context of the economic, social, and environmental costs of maintaining aging infrastructure. While dams can provide extensive benefits such as water management, power generation, and flood control, their environmental impacts can be detrimental, and much remains to be characterized. In Poland, there is growing concern about the future of the Wloclawek Dam and Reservoir, located on the Vistula River 110 km northwest of Warsaw. One of Poland's largest reservoirs, it has a volume of 408 million m^3 and an area of 70.4 km^2. This study explores the sediment transport and silting rates for the reservoir using a CCHE2D model and parameters including: channel width, average velocity, average depth, and Froude numbers at the cross-sections of the reservoir. The study findings provide a better understanding of the sedimentary conditions, and permit a precise delineation of three different zones in the reservoir: riverine, transitional, and lacustrine. The potential consequences of dam removal have been modelled and indicate that dramatic changes in hydraulic parameters will result, and a new 22.7 km^2 flood plain may form, which corresponds to 33% of the current reservoir area.

Key words Vistula River; Wloclawek Reservoir; fluvial processes; sediments transport; CCHE2D hydrodynamic model; dam removal

INTRODUCTION

Dams represent significant human modifications to fluvial environments, intercepting an estimated 25–30% of the global riverine sediment load, worldwide (Vorosmarty *et al.*, 2003). Lowland reservoirs are created by utilising the storage capacity of the river channel and flood plains. The consequences of sedimentation include, among others: silting of the reservoir, more difficult passage of ice during the winter, and accumulation of pollutants in the reservoir beds. Silting of lowland reservoirs shortens their life span, but even more problematic is the disruption of sediment transport causing channel degradation downstream from the dam. Common engineering practice is to design and operate reservoirs to reduce channel sedimentation and degradation, yet, like all forms of infrastructure, dams are subject to both aging and finally, retirement (Doyle & Havlick, 2009). It is estimated that the practical life span of a dam is a maximum of 120 years due to the gradual deterioration of concrete structures and reservoir sedimentation (American Society of Civil Engineers, 1997).

Few studies exist that document the consequences of the partial or full retirement of dams. In the USA more than 600 dams greater than 3 m in height have been removed in the past 20 years (Doyle & Havlick, 2009); still, inventories show approximately 78 000 remaining, so these structures are not disappearing, by any means. In China, dam construction was heavily promoted by the government starting after 1949 (Pisaniello, 2006); up until the end of 2006, 85 874 reservoirs were built in China; of these, 81 000 are small to medium scale. The majority of the small scale reservoirs (storage capacity less than 10 million m^3) were built in the 1950s and 1960s. Many display shortcomings in original planning, design, construction, and operation. Up to the end of 1999, about 42 000 small reservoirs had been determined to be defective in some way; while many have been modified, some 29 150 small reservoirs still have problems (He, 2005).

As dams approach the end of their designed lifespan, their negative aspects become more and more significant, especially relative to economic, environmental, and safety issues. Dam removal may be an effective way to decrease the risk of older dams, since it is generally difficult to cope with these problems using engineering measures. Although major international bodies are addressing issues associated with dam removal (World Commission on Dams, 2000), impacts on specific sites and locations remain difficult to generalize.

In light of the greater international attention directed toward dams, the sediment transport implications of removing a major dam in Poland are discussed in this paper. While the Wloclawek Dam originally was designed to be one of the 8 structures in the lower Vistula cascade, the others were never completed. In the recent years, it has become clear that the continued existence of the reservoir is threatened by the reduced stability of the dam's foundations caused by serious degradation of the river channel in the lower reach. Four possible courses of action have been proposed to reduce this risk, and one of these is removing the Wloclawek Dam entirely (WWF, 2001). The dam removal scenario will mobilize large volumes of sediment from the reservoir, with complex implications for downstream areas. Issues of sedimentation rates, nutrient loadings, and ecological impacts involve many indeterminate factors. This paper examines the patterns of sedimentation in the Vistula River lowlands in the Wloclawek Reservoir using a numerical model to project potential environmental consequences after dam removal or malfunction.

DESCRIPTION OF THE WLOCLAWEK RESERVOIR

The Wloclawek Reservoir, originally designed in the 1950s, was completed in 1968 and reached its operational capacity in 1970. The shape of the reservoir is generally narrow and elongated (Fig. 1). It covers approximately 70.4 km^2 and has a total volume of 408 million m^3, making it the largest lowland reservoir in Poland. At normal pool (corresponding to 57.3 m above sea level), the reservoir measures 56.8 km along the central axis of the original river channel (from river km 618.00 to 674.85). Detailed descriptions of the reservoir are reported elsewhere (Majewski, 1985; Babiński & Grześ, 1995; Łajczak, 1996; Kentzer, 2000; Giziński, 2003; Achrem & Gierszewski, 2007).

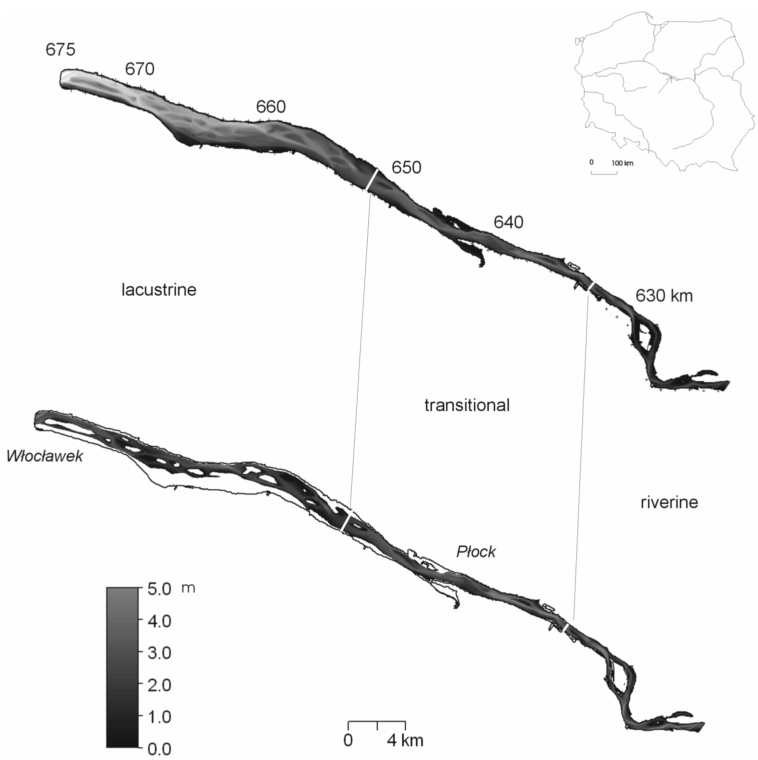

Fig. 1 Wloclawek Reservoir bathymetric maps representing scenarios with (upper part) and without the dam (lower part).

MATERIALS AND METHODS

The morphology of lowland reservoirs is controlled by river channel and flood plain geometry. Sedimentary processes are controlled by the overall flow velocity and vertical velocity profile. Measurement of these parameters is very difficult, and it is often impossible to provide a clear picture of the sedimentary effects of changing the discharge and the operating parameters of the dam (such as weirs crest levels, withdrawal rates at power plants, sluice discharge for compensation water, etc.). As a result, we elected to use a two-dimensional (2-D) hydrodynamic model for that purpose. Computational fluid dynamics models are used for estimating sedimentary consequences (Chang, 2008) as well as for predicting the ecological effects on a river after dam removal (Tomsic *et al.*, 2007).

Most of the data used in characterizing the reservoir's geometry was obtained in 1992 through echo soundings, performed at regular intervals, by the design bureau, "Hydroprojekt", on behalf of the Regional Water Authority (RZGW). A total of 81 fixed cross-sections were used, spaced 300–800 m apart, along the length of the reservoir and numbered sequentially from the dam proceeding upstream. These echo soundings were complemented by the authors in the summer of 2007, at the mouths of two tributaries (Skrwa Lewa and Skrwa Prawa). Measurements from the cross-sections were referenced to map datum Pulkowo 1942. Using ILWIS 3.3 GIS software, with additional information from historical topographic maps dating from the 1930s (scale 1:100 000) and 1960s (scale 1:25 000), a contour map of the reservoir bottom was produced. Manually establishing contour lines based on separate cross-sectional profiles was especially difficult in the lower part of the reservoir where there is no indication of a thalweg, and where many islands have been submerged.

A digital elevation model (DEM) of the reservoir bottom, with a lateral resolution of 5 m was used as input to a 2-D numerical hydrodynamic and sediment transport model called CCHE2D, developed at the National Center for Computational Hydroscience and Engineering (NCCHE) at the University of Mississippi. CCHE2D is a depth integrated 2-D model designed to simulate free surface flows and sediment transport. It is based on the depth-averaged Navier-Stokes equations, and is capable of simulating bedload or suspended sediment transport. Turbulent shear stresses were estimated using Boussineq's approximation, and introduction of turbulent eddy viscosity. Three different closure schemes were adopted. The set of equations was solved implicitly using the control volume approach and the efficient element method. The numerical calculations were carried out at the nodes of an irregular rectangular mesh. This model has been applied successfully to complex flows in natural channels, and has proven to be an efficient tool for hydraulic research and engineering projects (Jia *et al.*, 2002).

In this study, a major part of the Wloclawek Reservoir (56.8 km long, 69.1 km^2) was described by a mesh, which includes 50 grid lines along the reservoir and 534 cross-sections. The bottom elevations in the mesh nodes were determined from the DEM using the triangulation method. The upstream boundary condition was set as a steady flow that corresponded to the long term average discharge of 900 $m^3 s^{-1}$. The downstream condition was set at 57.3 m, the normal water level of the reservoir. A uniform Manning roughness coefficient was applied ($n = 0.03$) in this study. Verification of the model has been carried out through comparison of the flow velocity measurements performed at river km 646.5 with that produced by the numerical model. There is good agreement between the measured cross-sectional average velocity (v_m) of 0.157 ms^{-1} with the calculated value of 0.148 m s^{-1}. There also is reasonable agreement between the maximum measured vertical velocity of 0.224 m s^{-1} and the calculated value of 0.210 m s^{-1}. The agreement between measured and calculated water surface elevations also was very good, based on a comparison for river km 650–675 (Majewski, 1985). The maximum backwater elevation obtained from the model is 1.0 m while the literature value has been estimated at 0.75 m. This difference probably resulted from using a uniform Manning roughness coefficient in the model.

The CCHE2D model was also used to evaluate a dam removal scenario. For this analysis, the upstream boundary condition was set at 900 $m^3 s^{-1}$, and the downstream boundary condition set at a water level of 46.65 m a.s.l., corresponding to a pre-dam natural river, and a partial cross-sectional opening at the location of an earthen dam. Hydraulic conditions obtained from the model represent the initial stage of reservoir dewatering. The results of the CCHE2D model were transferred to the ILWIS 3.3 GIS program to produce a map of reservoir bathymetry and velocity distributions, and these characteristics were averaged and presented at selected cross-sections to create a longitudinal profile for the whole reservoir (Fig. 2).

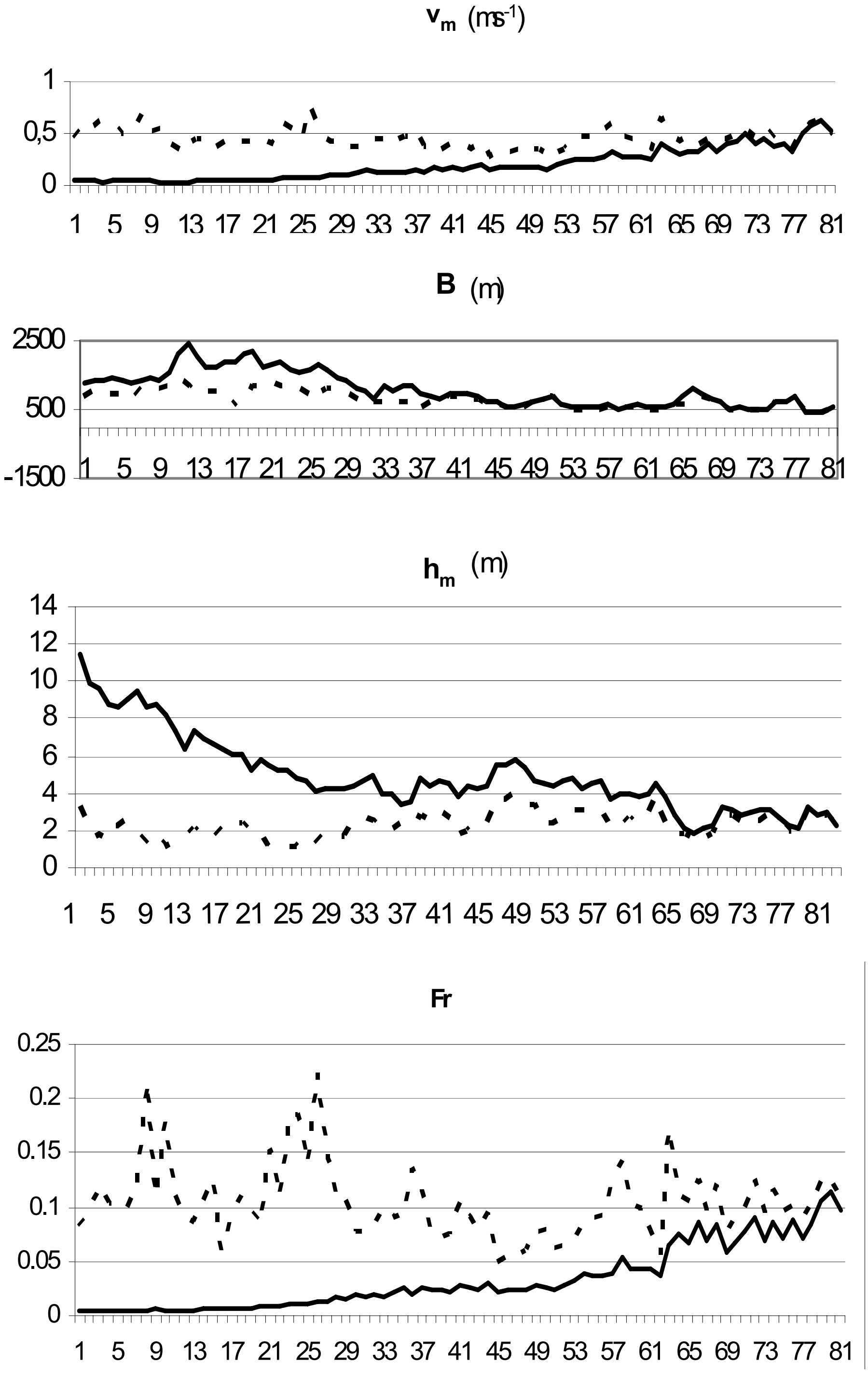

Fig. 2 Hydraulic parameters shown on Wloclawek reservoir longitudinal profiles (solid line – with the dam, dashed line – without the dam) expressed as cross-sectional values of: vm – average velocity, B – channel width, hm – average depth, Fr – Froude number, based on CCHE2D model scenarios.

RESULTS

The net sedimentation map was produced by calculating the difference between the DEMs dated 1971 and 1992, revealing changes in the bottom elevations. Over that period, the Wloclawek Reservoir retained 51.2 million m^3 of sediments, of which 32.9 million m^3 were eroded, resulting in a net accumulation of 18.3 million m^3. Accordingly, the average annual accumulation was 0.87 million m^3 (Bogucka & Magnuszewski, 2006). The calculated volume of the eroded material did not include that related to dredging that was carried out at the upper section of the reservoir after 1982 (Dziużyński & Magnuszewski, 1998). Various estimates of the volume of transported and accumulated sediment in the Wloclawek Reservoir, based on different data periods and on diverse methods, ranged from 0.62 to 2.51 million m^3 (e.g. Dębski, 1939, 1956; Brański, 1972; Wiśniewski, 1972; Brański & Dąbkowski, 1976; Babiński, 2002).

The upper reach of the reservoir includes transitional conditions from riverine to lacustrine, that are reflected in daily temperature fluctuations, wind induced waves, and the sedimentation of fine particles (Marzolf & Robertson, 2005). Based on the Wloclawek Reservoir morphometry, Skibinski (1985) identified three characteristic zones: riverine (km 618–632), transitional (km 632–653), and lacustrine (km 653–674.8). However, other researchers, identified only two zones, with the boundary at km 655; the flow velocity in the upstream segment was >1 m s^{-1} while that in the downstream segment was in the range of 0.1–0.4 m s^{-1} (Żbikowski, 2000). These values have not been confirmed either by measurement or model results.

In this study, the characteristic zones of the reservoir were defined using the hydraulic parameter as calculated using the CCHE2D model (Bogucka-Szymalska & Magnuszewski, 2007). Analysis of the bathymetry and velocity fields was performed at the same cross-sections for which cross-sectional echo soundings were available. In some cases, the cross-sectional profile was transformed to derive the profiles that were perpendicular to the longitudinal axis of the reservoir. The distributions of the longitudinal average velocity (v_m), channel width (B), and depth (h_m) in 1992 are shown in Fig. 1 In this figure, three characteristic reservoir zones can be discerned: riverine (km 617.9–632; profiles no. 56–81), transitional (km 632–649.8; profiles 27–56), and lacustrine (km 649.8–674.8; profiles 1–27); the corresponding hydraulic parameters are listed in Table 1.

Table 1 Predicted hydraulic parameters for characteristic reaches of the Wloclawek Reservoir based on the results from the CCHE2D model.

Reservoir reach	Location (km) profile (no.)	Width (m)	Average depth (m)	Average velocity (ms^{-1})
Riverine	617.9–632 56–81	400–1100	3.1	0.38
Transitional	632–649.8 27–56	540-1390	4.5	0.16
Lacrustine	649.8–674.8 1–27	1240 – 2410	7.0	0.05

Extensive river channel erosion below the dam has caused severe technical problems with the stability of the foundations of the weirs. As mentioned earlier, several remedial measures have been proposed, with the most radical being dam removal. The removal scenario raises questions about the likely route and profile of the river channel, the flood plain that may be formed, and the environmental impacts. The CCHE2D model results for such a scenario are shown in Fig. 2.

Based on a limited number of studies, primarily from the USA, incision processes following dam removal result in the mobilization of fine grained sediment, typically silts and clay, which tend to have localized and transient downstream effects such as pool infilling. Larger downstream impacts can result from incision into the coarse grained sediment at the upstream end of the transitional and riverine reaches (Evans *et al.*, 2002). Studies have suggested that low head dam removal can result in upstream erosion of the channel bed and streambanks, significantly increasing sediment loads, with most of these materials eroding within the first 3 years (Wells *et al.* 2007). Of course, the composition of the streambank soils is an essential variable in this situation as recent insights into the role of sediments from relict mill ponds have demonstrated (Walter & Merritts, 2008). Furthermore, the nature of the material released after dam removal also is a concern; for example, severe environmental problems resulted from the release of PCB-contaminated sediments in the Hudson River after removal of the Fort Edward Dam in New York (Shuman, 2006). A related problem occurred on the Sandusky River (Ohio, USA) when removal of the Ballville Dam created the potential problem of mobilising contaminated sediment. Problem resolution would require dredging, or the downstream release of some 0.35 million m^3 of sediment to re-establish the river channel (Evans & Gottgens, 2007).

In the case of the Wloclawek Dam, new flood plains would likely emerge after dam removal, assuming no severe bank erosion took place. The new flood plains are expected to have an area of 22.7 km^2, which corresponds to 33% of the current area of the reservoir (Fig. 1). Achrem & Gierszewski (2007) reported that the dominant types of reservoir bottom sediments include: loam (49.9 %), sandy loam (18.9 %), loamy sand (11.3 %), and sand (11.1 %). The organic content of the bottom sediments ranges from 5 to 15%. Figure 2 shows that the most dramatic changes in river hydraulics (channel width and depth, average velocity), after dam removal, is likely to occur in the lacustrine zone.

Recent studies on the chemistry of Vistula sediments collected between Wyszogród and Toruń reveal heavy metal concentrations in the Wloclawek Reservoir that are substantially above geochemical background (Szwarczewski, 2000). A study of Wloclawek Reservoir lacustrine segment bottom sediments showed that concentrations of Cd (0.5–12.3 ppm) and Hg (0.011–6.0 ppm) are markedly higher than background (Achrem & Gierszewski, 2007). It was also noted that the concentrations were not uniform; they were generally lower after the spring flood, when higher velocities led to greater sediment fluxes. The highest metal levels were found in the lacustrine zone, and associated with submerged flood plains. Szwarczewski (2000) found that the deeper layers of reservoir sediments (15–25 cm downcore) are more contaminated than at the surface, highlighting the problem of highly contaminated but buried sediments.

The problem of the stability of a newly created channel after dam removal could be assessed by comparing the hydraulic parameters in the reservoir with those in a free flowing river (Table 2). According to Skibinski's (1976) empirical formula developed for the Vistula River, bedload transport is very strongly related to the Froude number (Fr). Therefore, an increase in flow velocity and Fr following, dam removal would likely lead to extensive bedload transport, and erosion in the lacustrine zone.

Table 2 Comparison of the Wlocalwek Reservoir area hydraulic parameters area, with and without the dam based on CCHE2D model scenarios.

Average hydraulic parameter in the reach	riverine reach (km 617.9–632) (profile no. 56-81)		transitional reach (km 632–649.8) (profile no. 27–56)		lacrustine reach (km 649.8–674.8) (profile no. 1–27)	
	with dam	without dam	with dam	without dam	with dam	without dam
v_m (ms^{-1})	0.382	0.480	0.163	0.39	0.048	0.498
B (m)	640	570	910	740	1690	910
h_m (m)	3.0	2.4	4.5	2.6	7.2	1.8
Fr – average cross-section Froude number	0.071	0.107	0.024	0.086	0.007	0.122

v_m: average cross-sectional velocity; B: average cross-sectional width; h_m: average cross-sectional depth; Fr: average cross-sectional Froude number.

CONCLUSIONS

Hydrodynamic modelling using the 2-D CCHE2D model provides valuable information on sedimentary environments, and makes it possible to illustrate the consequences of the removal of the Wloclawek Dam and reservoir system. Three hydraulically distinct zones were identified in the reservoir – lacustrine, transitional, and riverine. The lacustrine and transitional zones were found to provide good depositional conditions on former flood plains and on channel macro-forms. A hypothetical dam removal scenario for the Wloclawek Dam illustrates the potential for creating a new and dynamic river channel, with new flood plains covered by fine sediments, and estimated to cover an area of 22.7 km^2. Contaminated sediments deposited on the new flood plains, as well as their likelihood of being eroded, could create environmental problems in the lower reaches of the Vistula River. The movement of contaminated sediments is one of the negative consequences identified by the dam removal scenario. According to the Polish National Commission for Environmental Impact Assessment (Kraszewski, 2008), there is a need to work out a methodology for predicting the consequences of dam removal. Polish law now requires that any new plans for dam construction projects should include an assessment of the potential environmental impacts at the end of a reservoir's life expectancy, and studies such as this one could be useful in that regard. Furthermore, results from this study may be applicable to other large lowland reservoirs in the world.

Acknowledgements We wish to acknowledge and thank Warsaw Regional Water Authority (RZGW) for providing bathymetric survey data. Professor Mustafa Altinakar and Dr Yaoxin Zhang (National Center for Computational Hydroscience and Engineering, School of Engineering. The University of Mississippi University) for permitting use of the CCHE2D model and their kind assistance in solving computational issues. This study is supported by the Science and Technology Commission of Shanghai Municipality, Foundation for Science Cooperation between Sino-Poland, no. 072407031.

REFERENCES

Achrem, E. & Gierszewski P. (2007) *Zbiornik Włocławski* [Wloclawek Reservoir] Inspekcja Ochrony Środowiska, Biblioteka Monitoringu Środowiska, Bydgoszcz, Poland.

American Society of Civil Engineers (1997) *Guidelines for Retirement of Dams and Hydroelectric Facilities*. ASCE, New York, USA.

Babiński, Z. (2002) *Wpływ zapór na procesy korytowe rzek aluwialnych* [Impact of dams on bed processes in alluvial rivers, in Polish] Akademia Bydgoska, Bydgoszcz, Poland.

Babiński, Z. & Grześ, M. (1995) Monografia hydrologiczna zbiornika stopnia wodnego Włocławek [Hydrological Monography of the Włocławek Stage of Fall Reservoir, in Polish]. *Prace Geograficzne* IGiPZ PAN **30**, 15–47.

Bogucka, M. & Magnuszewski, A. (2006) The sedimentation processes in Wloclawek Reservoir. *Miscellanea Geographica* 12, 95–101.

Bogucka-Szymalska, M. & Magnuszewski, A. (2007) Zastosowanie modelu NCCHE2D do oceny warunków sedymentacji w Jeziorze Włocławskim [Application of NCCHE2D model for description of sedimentation processes in Wloclawek reservoir] *Prace i Studia Geograficzne UW* **38**, 105–116 (in Polish).

Brański, J. (1972) Bilans transportu rumowiska unoszonego wzdłuż biegu Wisły [Balance of the suspended sediments carried down the Vistula] *Gospodarka Wodna* 3 (in Polish).

Brański, J. & Dąbkowski, S. L. (1976) Uwagi o prognozowaniu zamulania zbiorników wodnych na rzekach nizinnych [Remarks on Forecasting Siltation in Water Reservoirs in Lowland Rivers] *Archiwum Hydrotechniki* 3 (in Polish).

Chang, H. H. (2008) Case study of fluvial modeling of river responses to dam removal. *J. Hydraul. Engng ASCE* **134**(3), 295–302.

Dębski, K. (1939) O transporcie i osadzaniu aluwiów [On transport and sedimentation of alluvial deposits]. *Gospodarka Wodna* 2 (in Polish).

Dębski, K. (1956) Gdzie leży bezpieczeństwo Gdańska i delty Wisły [The security of Gdańsk and the delta of the Vistula, in Polish] *Gospodarka Wodna*. 6 (in Polish).

Doyle, M. W. & Havlick, D. G. (2009) Infrastructure and the environment. *Ann. Rev. Environ. Resour.* **34**, 349–373.

Dziurzyński, T. & Magnuszewski, A. (1998) Nowa metoda zobrazowania i obliczeń tempa sedymentacji w Jeziorze Włocławskim za pomocą systemu geoinformacyjnego. [New method of visualization and calculation of sedimentation in Wloclawek Reservoir with the use of GIS]. *Gospodarka Wodna* **6**, 212–216.

Evans, J. E., Levine, N. S., Roberts, S. J., Gottgens, J. F., & Newman, D. M. (2002) *J. Am. Water Resour. Assoc.* **38**(6), 1549–1565.

Evans, J. E. & Gottgens, J. F. (2007) Contaminant stratigraphy of the Ballville reservoir, Sandusky River, NW Ohio: implications for dam removal. *J.Great Lakes Res.* **33**(2), 182–193.

Giziński, A. (2003) Środowiskowe skutki regulacji rzek [The environmental consequences of river regulation, in Polish]. *Gospodarka Wodna* 11, 470-478 (in Polish).

He, X. Y. (2005) Census and preliminary analysis of dam accidents occurred in China. In: Proc. 2005 annual conference of Chinese Hydraulic Engineering Society.

Jia, Y., Wang, S. S., & Xu, Y. (2002) Validation and application of a 2D model to channels with complex geometry. *Int. J. Computational Engng Sci.* **1**, 57–71.

Łajczak, A. (1996) Reservoir sedimentation problems in the Vistula River basin, Poland. *Erosion and Sediment Yield: Global and Regional Perspectives* (ed. by D. E. Walling & B. W. Webb) (Proc. Exeter Symposium). IAHS Publ. 236. IAHS Press, Wallingford, UK.

Kentzer A. (2000) Hydrogeochemistry of the Vistula between Płock and Toruń. *Acta Universatis Nicolai Copernici. Limnological Papers* no. 21, 33–42.

Kraszewski. A. (2008) Stanowisko Krajowej Komisji do Spraw Oddziaływania na środowisko w sprawie oceny wariantów przedsięwzięć zapewniających bezpieczeństwo ekologiczne stopnia we Włocławku. [Statement of National Commission for Environmental Impact Assessment on evaluation of scenarios for Wloclawek reservoir ecological safety improvement]. *Problemy Ocen Środowiskowych* **43**, 48–50 (in Polish).

Majewski, W. (ed.) (1985) *Powódź zatorowa na Wiśle w rejonie Zbiornika Włocławek w zimie 1982 r.* [The Vistula ice jam flood near the Włocławek Reservoir in the winter of 1982]. Wydawnictwo Geologiczne, Warszawa, Poland (in Polish).

Marzolf, G. R. & Robertson, D. M. (2005) Reservoirs. In: *Encyclopedia of Hydrological Sciences* (ed. by M. G. Anderson). John Wiley & Sons. Ltd, New York, USA.

Pisaniello, J. D., Wu, Z. & McKay, J. M. (2006) Small dams safety issues – engineering/policy models and community responses from Australia. *Water Policy* **8**, 81–95.

Shuman, J. R. (2006) Environmental considerations for assessing dam removal alternatives for river restoration. *Regulated Rivers: Research & Management* **11**(3–4), 249–261.

Skibiński, J. (1976) *Próba ilościowej oceny intensywności transportu rumowiska wleczonego w rzekach środkowej Polski*. [A trial quantitative estimation of bedload discharge in the rivers of central Poland]. Zeszyty Naukowe SGGW. Warszawa, Poland (in Polish).

Skibiński, J. (1985) *Charakterystyka morfologiczna Wisły na odcinku Modlin-Włocławek oraz zmiany powstałe w ukształtowaniu dna w wyniku spiętrzenia wody w Zbiorniku Włocławskim* [The morphological characteristics of the Vistula between Modlin and Włocławek and changes in the river bottom caused by damming water in the Włocławek Reservoir, in Polish]. In: Powódź zatorowa na Wiśle w rejonie Zbiornika Włocławek w zimie 1982 r. [The Vistula ice jam flood near the Włocławek Reservoir in the winter of 1982, in Polish], (ed. by W. Majewski). Wydawnictwo Geologiczne, Warszawa, Poland (in Polish).

Szwarczewski, P. (2000) Changes in the heavy metal content in river alluvia of Lower Vistula during the last 100 years. *Miscellanea Geographica* **9**, 137–146.

Tomsic, C. A., Granata, T. C., Murphy, R. P. & Livchak C. J. (2007) Using a coupled eco-hydrodynamic model to predict habitat for target species following dam removal. *Ecol. Engng* **30**, 215–230.

Vorosmarty, C. J., Meybeck, M., Balazs, F., Sharma, K., Green, P., & Syvitski, P. M. (2003) Anthropogenic sediment retention: major global impacts from registered river impoundments. *Global and Planetary Change* **39**, 169–190.

Walter, R. C. & Merritts, D. J. (2008) Natural streams and the legacy water-powered mills. *Science* **319**, 299–304.

Wells, R. R., Langendoen, E. J. & Simon A. (2007) Modeling pre- and post-dam removal sediment dynamics: the Kalamazoo River, Michigan. *J. Am. Water Resour. Assoc.* **43**(3), 773–785.

Wiśniewski, B. (1972) Ilość rumowiska unoszonego i wleczonego w rzekach polskich [Volume of bedload and suspended sediment carried by Polish rivers]. *Gospodarka Wodna* 10–11 (in Polish).

World Commission on Dams (2000) *Dams and Development*. Earthscan, London, UK.

WWF – World Wildlife Fund, (2001) *Studium kompleksowego rozwiazania problemów stopnia i zbiornika Włocławek* [Study on complex solution of Wloclawek dam and reservoir problems]. WWF, Światowy Fundusz na Rzecz Przyrody, Warszawa, Poland (in Polish).

Żbikowski, J. (2000) Macrozoobenthos of the Vistula in the section from Wyszogród and Toruń. Acta Universatis Nicolai Copernici. Nauki Matematyczno-Przyrodnicze. *Prace Limnologiczne* **105**, 2175–2184.