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Estimating the annual sediment yield of a small agricultural catchment in central Poland

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Abstract The annual sediment yield of a small (91 km^2) agricultural catchment in central Poland has been estimated, based on river flow measurements and catchment characteristics, and verified by reservoir surveys. Although soil erosion rates and sediment yields in this part of Poland are generally seen as low by global standards, reservoir sedimentation is a problem and there is a need to develop and validate a method for estimating catchment sediment yields. In this investigation, the suspended sediment input to a reservoir, has been estimated using the Universal Soil Loss Equation coupled with a sediment delivery ratio (USLE-SDR). The annual bed load has been estimated based on the flow duration curve and three different bed load formulae. The reservoir surveys were carried out four times between 1980 and 2009. Between 1980 and 2009 the reservoir lost approx. 13% of its capacity. A close agreement was found between the amount of sediment deposited in the reservoir and the sediment input estimated using the USLE-SDR and the bed-load formulae.

Key words sediment yield; sediment delivery; sediment budget; reservoir sedimentation; USLE; bed load formulae; Poland

INTRODUCTION

Estimation of the sediment yield from small catchments is important both for hydro-engineering practice and for environmental prediction and modelling. Catchment sediment budgets and sediment yields have attracted considerable attention in recent years in the context of both their environmental importance and the need to develop an improved understanding of the physical processes involved and therefore provide more accurate predictions (Horowitz & Walling, 2005; Boardman, 2006; Kinnell, 2008; Peng, 2008; Sadeghi *et al*., 2008; Walling & Collins, 2008; Banasik *et al*., 2010; Parsons, 2012). In Poland, studies of sediment yields and sediment budgets have been undertaken for large rivers, based on the data available from a 40-year suspended sediment monitoring programme undertaken at about 50 river gauging stations by the Institute of Meteorology and Water Management (IMGW) during the period 1951–1990 (Brański & Banasik, 1996; Banasik *et al*., 2005). However, because of the scale of the catchments involved, such studies can provide only very general information on the intensity of the processes and the key controls.

The aim of the work described in this contribution is to compare the estimate of sediment yield from a small agricultural catchment, derived using the Universal Soil Loss Equation coupled with a sediment delivery ratio (USLE-SDR) and estimates of annual bed load transport provided by selected bed-load transport formulae, with the amount of sediment deposited in a reservoir at the catchment outlet. Annual bed load transport has been estimated on the basis of the flow duration curve and three different formulae. The first is the well-known Meyer-Peter & Mueller (1948) formula, the second the Skibinski (1976) formula, developed using measurements of sediment transport in large lowland rivers of Poland in the 1970s, and the third the Popek (2006) formula, based on intensive bed load monitoring on a lowland small river. The dam of the reservoir was constructed in 1976. The first reservoir survey was carried out in 1979–1980, when the reservoir volume was estimated to be 252 000 m^3. The subsequent surveys were carried out in 1991, in 2003 and in 2009.

CATCHMENT CHARACTERISTICS AND SEDIMENT DELIVERY

The study catchment

The Zagozdzonka catchment (Fig. 1) is a small lowland agricultural catchment, located in central Poland, about 100 km south of Warsaw. Hydrological investigations of the Zagozdzonka River at Plachty (51°26′43.8″N; 21°27′35.6″E), have been carried out by the Department of Water Engineering of Warsaw University of Life Science (WULS) since 1962. The catchment area is 82.4 km^2 at the Plachty gauging station (upstream of A, Fig. 1), whereas the catchment area above the dam of the "Staw Gorny" Reservoir is 91.4 km^2.

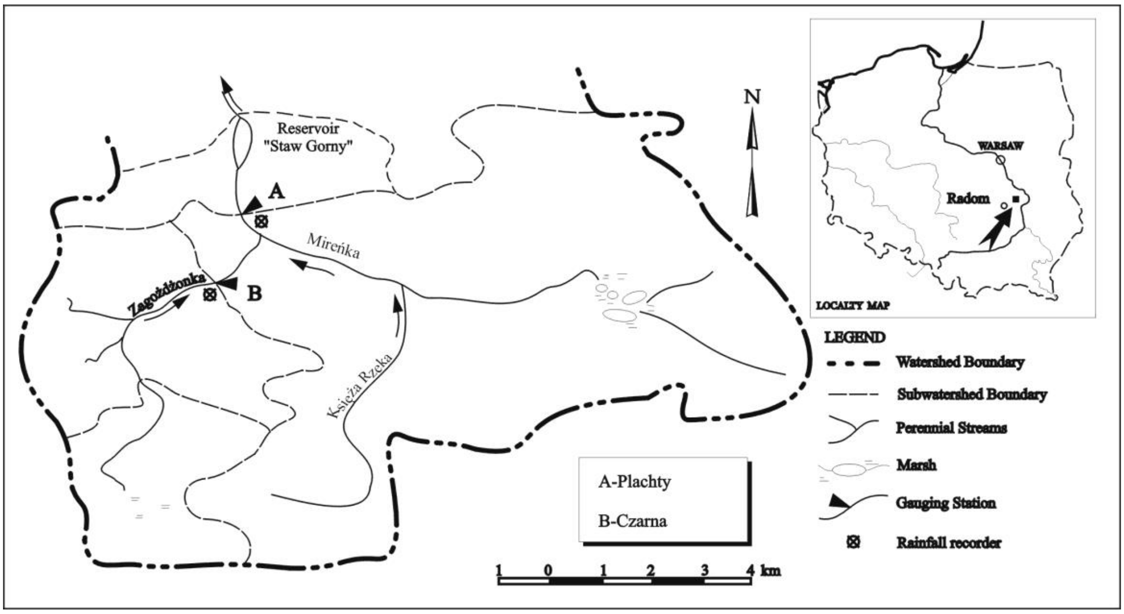

Fig. 1 Location map of the Zagozdzonka catchment, showing the "Staw Gorny" Reservoir and the Plachty and Czarna gauging stations.

Rainfall and runoff

Since the river gauge at Plachty is in a rated section (Fig. 2), each year 8–12 flow gauging measurements have been undertaken to establish and update the rating curve. The mean annual precipitation and runoff for the period 1963–2011 are estimated at 612 mm and 107 mm, respectively, based on data collected by the Department of Water Engineering of WULS at the Plachty and/or Czarna gauging stations, except for the precipitation data for 1963–1982, which were taken from available publications of the Polish hydro-meteorological service (IMGW) for the nearest raingauge at Zwolen (located about 15 km west of the Czarna gauging station). The maximum and minimum values of annual precipitation are 941 mm (1974) and 414 mm (1991), respectively. The maximum annual runoff of 209 mm was recorded in 1980 and the minimum of 52 mm in 1992. This variability in annual precipitation and runoff, as well as the mean values for the whole period of investigation, i.e. 1963–2011, and for the period 1980–2009 (i.e. between the first and the last reservoir surveys) are presented in Fig. 3. Annual runoff coefficients (ratio of runoff to precipitation) for the catchment of the Plachty gauging station range from 0.089 (1992) to 0.324 (1979), with a mean value of 0.174. The mean annual suspended sediment concentration (SSC) is relatively low and is estimated to be ~14 mg L^{-1}. However, during floods the SSC increases and the maximum recorded value is 220 mg L^{-1} (Hejduk, 2001).

Topography, land use and soils

The lowland Zagozdzonka catchment has topography typical of this part of Poland. Absolute relief is approx. 36 m for the catchment upstream of the Plachty gauging station (upstream of A, Fig. 1)

Fig. 2 Views of the gauging station at Plachty Stare (photos are looking downstream: top photograph – during a low flow period in May 2006; bottom – during a snowmelt period in 2010, when the discharge was close to the 2-year flood).

and 37.8 m for the catchment upstream of the reservoir dam (146.70–184.5 m a.s.l.). The mean slopes of the main channels range from 2.5 to 3.5 m per 1000 m. Local closed depressions, which do not contribute to direct runoff and sediment yield from the catchment, constitute a significant part of the area, i.e. 19.8 km^2 upstream of the Plachty gauging station and the reservoir dam. Land use within the reservoir catchment is dominated by arable land (small grain and potatoes), which occupies about 54% of the catchment, and about 33% is covered by forest, 12% by pasture and 1% by roads and surface water (Banasik *et al*., 1995). Sandy soils are dominant in the catchment area (loamy sand, 32%; light loamy sand, 56%; and organic soils, 12%).

Estimation of sediment input to the reservoir

The suspended sediment input to the reservoir was estimated by applying the USLE-SDR procedure to the reservoir catchment, and the bed load contribution was computed using the three formulae indicated above in association with hydraulic and hydrological data for the river channel at the Plachty gauge.

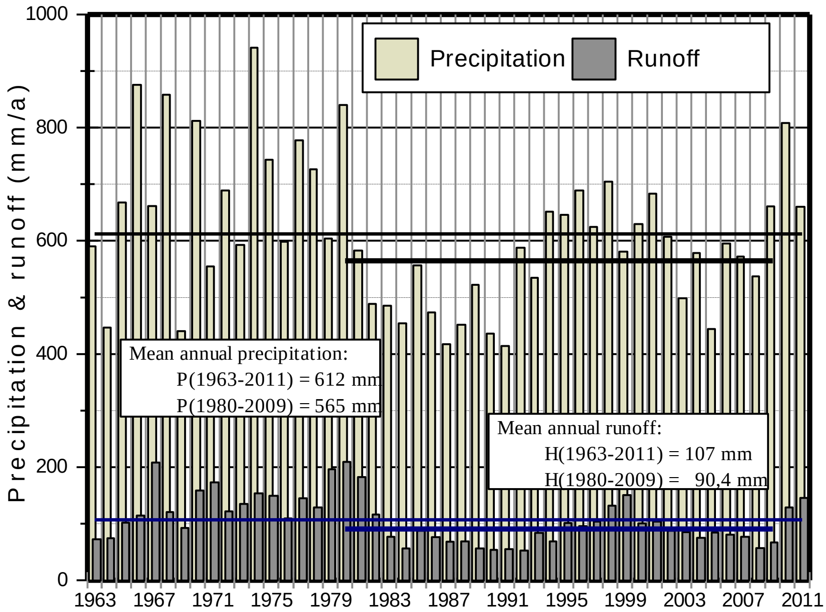

Fig. 3 Annual precipitation and runoff for the Zagozdzonka catchment upstream of the Plachty Stare gauge for the period between the first and the last reservoir surveys in 1980 and 2009, compared with the longer-term record for the period 1963–2011.

When applying USLE to regions other than the USA, there is a need to establish regionally sensible parameters, e.g. the rainfall and runoff erosivity, *R*. This had already been done for Polish conditions in a previous study, which used the precipitation records for 1960–1988 (Banasik & Górski, 1993; Banasik *et al*., 2001). The form of the Universal Soil Loss Equation (Wischmeier & Smith, 1978) and its parameters are as follows:

$$E = R \cdot K \cdot LS \cdot C \cdot P \quad (1)$$

where:

E – annual soil loss per unit area (Mg ha^{-1} year^{-1}),
R – the rainfall and runoff erosivity (JE year^{-1}; JE = (MJ ha^{-1})(cm h^{-1}) – the unit of erosivity),
K – soil erodibility (Mg ha^{-1} JE^{-1})
LS – topographic factor (-),
C – cover and management factor (-),
P – support practice factor (-).

By using the USLE together with the sediment delivery ratio *SDR*, the annual sediment yield from the catchment above the reservoir can be estimated as:

$$Y_r = SDR \cdot E \cdot A_E \quad (2)$$

where Y_r is annual sediment yield from the catchment of the reservoir (Mg year^{-1}), *SDR* is sediment delivery ratio, assumed according to Roehl (1962) as a function of catchment area (-), and A_E is the active area of catchment (ha).

The parameters of equation (2) were estimated for the catchment area of the Staw Górny Reservoir within the Zagożdżonka catchment, using topographic, soil and land use maps, as follows: S*DR* = 0.13, A_E = 7180 ha, R = 77.1 JE year^{-1}, K = 0.247 Mg ha^{-1} JE^{-1}, LS = 0.393, $C \cdot P$ = 0.08 (Banasik *et al*., 1995). These provide an estimate of the annual sediment input to the reservoir from its catchment Y_r of 503 Mg year^{-1}. Assuming that the density of deposited suspended sediment in the Staw Górny Reservoir is 0.71 Mg m^{-3} (Wiśniewski, 1969) and that the reservoir trap efficiency is 100%, this sediment input is equivalent to a volume of suspended sediment deposits in the reservoir of 708 m^3 year^{-1}.

The mean annual bed load transport was estimated using the flow duration curve for the 30-year period 1980–2009, and the schematic channel geometry at the Plachty gauging station (i.e. bottom width = 2.5 m, Manning roughness coefficient of the main channel $n = 0.037$, depth of the trapezoidal channel $h = 1.2$ m) as input to the three different formulae used for calculating specific bed load transport intensity:

(a) Meyer-Peter-Mueller (1948) formula

$$q_r = \frac{25{,}1}{(1-p)(s-1)}\left[\left(\frac{k_s}{k_r}\right)^{\frac{3}{2}} R_s \cdot J - 0.047(s-1)\cdot d_m\right]^{\frac{3}{2}} \quad (3)$$

where:
q_r – specific bed load transport intensity (m^3 s^{-1} m^{-1})
p – porosity of deposited bed load sediment (-),
s – relative density of sediment ($s = \rho_s/\rho_w$ – sediment density / water density) (-),
k_s – Strickler's coefficient of bed roughness (m$^{1/3}$ s^{-1}),
k_r – the coefficient of particle roughness, equal to $26/d_{90}^{1/6}$,
d_{90} – the particle size at which 90% of the bed mixture is finer (m),
R_s – the hydraulic radius of that part of the cross-section apportioned to the bed load transport (m),
J – the energy gradient (-),
d_m – the effective diameter of the bed-material mixture (m), $d_m = \sum_{i=1}^{n} d_i \Delta p_i$
d_i – the mean grain diameter of the sediment in size fraction i (m),
Δp_i – the fraction, by weight, of bed material in a given size fraction (-).

(b) Skibiński (1976) formula, which was developed on the basis of bed load transport measure ments for the Vistula River and its tributaries in central Poland:

$$q_r = 6.18\cdot 10^{-5}\cdot C_d^{0{,}134}\cdot h^{-0{,}223} v_s^{3{,}40} \quad (4)$$

where:
q_r – specific bed load transport intensity (m^3 s^{-1} m^{-1})
C_d – coefficient of grain uniformity according to Kollis, $C_d = \frac{d_{90}\cdot d_{10}}{d_{50}^2}$, (-)
h – water depth (m),
v_s – mean velocity (m s^{-1}).

(c) Popek (2006) formula, recently developed and based on measurements in a small lowland river:

$$\frac{q_b}{\sqrt{(s-1)gd_{50}^3}} = \left[0.0792 + \frac{5.88\cdot 10^{-5} q}{\sqrt{(s-1)gd_{50}^3}}\right]^2 \quad (5)$$

where:
q_b – specific bedload transport (m^3 s^{-1} m^{-1}),
q – specific water discharge (m^3 s^{-1} m^{-1}),
g – the acceleration of gravity (m s^{-2}),
d_{50} – the median particle diameter of bed material (m).

The estimates of the total mean annual sediment input to the "Staw Gorny" Reservoir based on the above calculations are given in Table 1.

Table 1 Mean annual sediment input to the Staw Górny Reservoir.

Formula used in calculation	Volume of deposited sediment (m^3)		
	Bed load	Suspended load	Total
USLE-SDR and MPM formula	321	708	1 029
USLE-SEDR and Skibiński formula	305	708	1 013
USLE-SDR and Popek formula	220	708	928

RESERVOIR SURVEY RESULTS AND CONCLUDING REMARKS

The Staw Górny Reservoir was constructed in 1976. Its original purpose was supply of water to a local chemical factory. Another purpose, which has since become the main use of the reservoir, is recreation for the 19 000 inhabitants of the town of Pionki. The original reservoir volume V_0 was 252 000 m^3 at the normal impoundment water level, NPP, of 146.70 m a.s.l. The reservoir area A_R is 14 ha, the maximum water depth is about 2.60 m and the total length of the reservoir L_R is 900 m. Figure 4 presents a schematic representation of the Staw Górny Reservoir range layout used to survey the changing storage volume. Construction of this reservoir has caused sediment deposition both within the reservoir as well as in the reach of the river channel immediately above the reservoir. Bed elevation changes have been observed at the Plachty gauge, which is located approx. 1300 m upstream of the reservoir (Fig. 5). By 1986 (i.e. 10 years after the construction of the dam), the mean bed elevation at the Plachty gauge had increased by 42 cm. The base of the channel at this location is formed of sands with a median particle diameter d_{50} of 0.5 mm.

Reservoir surveys are considered to be the most reliable technique available for assessing sedimentation intensity, updating the current storage characteristics of a reservoir and estimating sediment yield from the upstream catchment (Strand & Pemberton, 1982; Morris & Fan, 1998). The first bed survey of the Staw Górny Reservoir was conducted during the period November

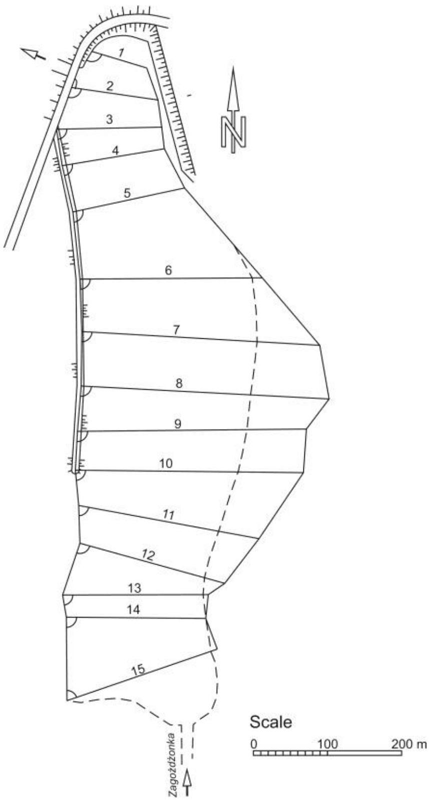

Fig. 4 Layout of the survey range for the Staw Górny Reservoir.

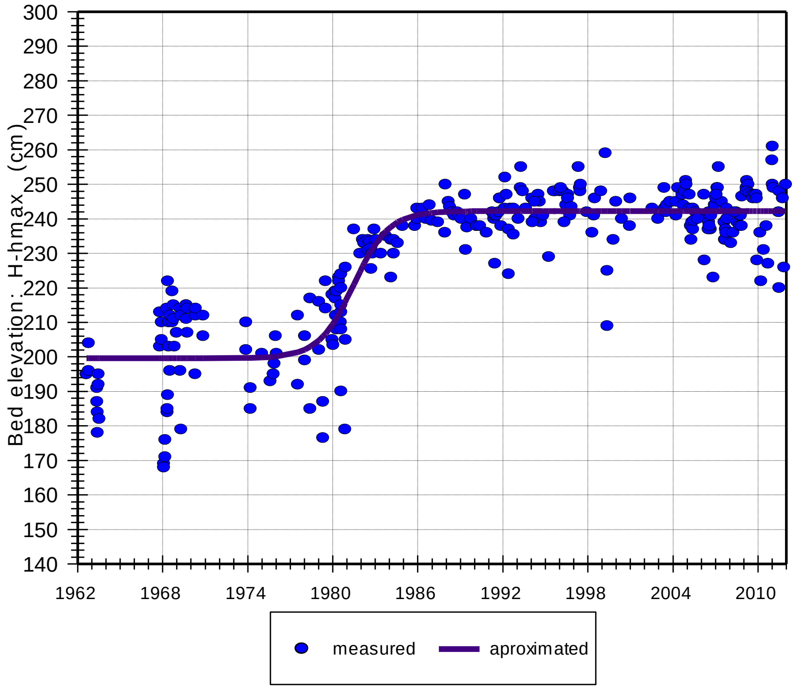

Fig. 5 Variation of the river bed elevation at the Płachty Stare gauge during the period 1962–2011.

Table 2 The volume of sediment deposited in the Staw Górny Reservoir.

Period between measurements	Volume of sediment deposits (m^3)	
	Total	Annual
1980–1991*	14 700 + 1 300**	1 330
1991–2003	11 600	970
2003–2009	4 900	820
1980–2009*	32 500	1 080

* The period also includes the year 1980 as the first survey was carried out at the beginning of that year.
** Estimate of deposition in the river channel between the gauging station and the reservoir.

1979–February 1980, using the range line method (Banasik & Mordziński, 1982). A base line was established by fixing permanent markers along the left side of the reservoir and cross-sections were referenced by distance and direction angles to the base line as shown on Fig. 4. The same fixed range layout was used in successive surveys conducted in June 1991 and in September 2003 (Banasik *et al.*, 2005). The last survey in August 2009 was carried out using the contour line method. Measurements undertaken in 2003 and in 2009 were conducted using a survey vessel equipped with a hydrographic system comprising an echo-sounder unit and a Global Positioning System (GPS) receiver. The 200 kHz echo sounder transducer makes it possible to survey water depths in the range 0.3–99.9 m with an accuracy of ±0.01 m. The eight-channel GPS receiver permits the position of sounding points to be determined with an accuracy of ±1 m. All measured values of water depth, together with the sounding position, are then logged internally every two seconds. The results obtained from the sequential surveys of Staw Górny Reservoir are given in Table 2. Area and capacity curves for the reservoir, calculated on the basis of surveys conducted in 1980 and 2009, are shown in Fig. 6.

Based on the data presented in Table 2 and shown in Fig. 6, the reservoir had lost 32 500 m^3 of its volume, i.e. 12.9% of its original capacity in 1980. This indicates an average annual loss of reservoir capacity of 1080 m^3 or 0.43%. This is equivalent to a mean annual specific sediment

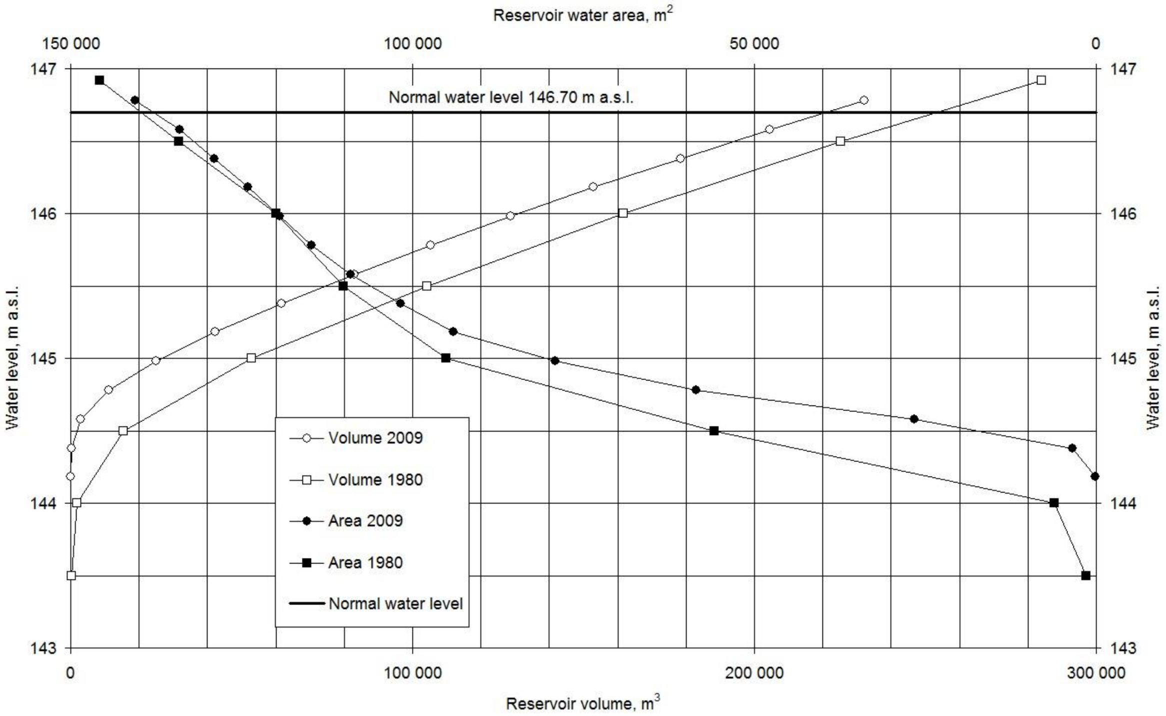

Fig. 6 Area and capacity curves for the Staw Górny Reservoir.

yield of 11.8 m^3 km^{-2} (1080 m^3/91.4 km^2). This value could be higher for the longer-term mean, since, on average, the period 1980–2009 was dryer than the longer period covered by hydrological observation in this catchment (i.e. 1963–2011). In terms of mean annual precipitation it was 7.3% dryer (565 mm *vs* 612 mm) and in terms of mean annual runoff, 15.6% dryer (90.4 mm *vs* 107 mm).

The values of total sediment input to the reservoir (suspended and bed load) estimated using the USLE-SDR and bed-load formulae are very close to the measured amount of annual deposition. Since, in all three cases, the estimated sediment inputs are smaller than the measured deposition, use of the MPM formula appears to provide the result closest to the measured value.

This comparison was carried out using approximate values for trap efficiency and for several of the variables involved in estimating the sediment input to the reservoir. These include the sediment delivery ratio and the bulk density of deposited suspended sediment. Taking account of organic matter content would probably decrease the difference between the estimated and measured values of sediment input to the reservoir, although inclusion of sediment compaction, as discussed by Morris *et al*. (2007) and Dugga & Soni (2005), would decrease the estimated value of suspended sediment input and thus increase the difference between the estimated and measured values.

The results presented indicate that, when coupled with a bed-load formula, the USLE-SDR approach is likely to provide meaningful estimates of sediment yield and sediment inputs to reservoirs for small lowland catchments with conditions similar to the study catchment. Scope exists to increase the accuracy of prediction by refining the procedures for estimating a number of the variables and parameters used in the estimation procedures.

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REFERENCES

Banasik, K., Barszcz, M. & Brański, J. (2005) Major components of a sediment budget for four river catchments in Poland. In: *Sediment Budgets II* (ed. by A. J. Horowitz & D. E. Walling), 32–36. IAHS Publ. 292. IAHS Press, Wallingford, UK.

Banasik, K. & Gorski, D. (1993) Evaluation of rainfall erosivity for East Poland. In: *Runoff and Sediment Yield Modelling* (ed. by K. Banasik & A. Żbikowski) (Proceedings of an International Symposium, Warszawa, September 1993), 129–134. Warsaw Agricultural University Press, Warsaw, Poland.

Banasik, K., Gorski, D. & Mitchell, J. K. (2001) Rainfall erosivity for East and Central Poland. In: *Soil Erosion Research for the 21th Century* (Proc. Int. Symp., 3–5 January 2001, Honolulu) (ed. by J. C. Ascough & D. C. Flanagan), 279–282. American Society of Agricultural Engineers, St Joseph, Michigan.

Banasik, K., Hejduk, L. & Popek, Z. (2005) Sediments problems of small river catchments and reservoir in Poland. *Publications of the Institute of Geophysics, Polish Academy of Sciences*, Monograph vol. E-5 (387), 179–207.

Banasik, K., Horowitz, A. J., Owens, P. N., Stone, M. & Walling, D. E. (2010) *Sediment Dynamics for a Changing Future*. (Proceedings of the Warsaw Symposium, June, 2010), iii–iv. IAHS Publ. 337. IAHS Press, Wallingford, UK.

Banasik, K. & Mordziński, S. (1982) Wyniki badan i prognoza zamulania malego zbiornika wodnego (Investigation results and prediction of small reservoir siltation). In: *Selected problems of hydraulic structures – designing and constructing* (in Polish). (Proceedings of a National Symposium, Warszawa, September 1982), 62–77. Warsaw Agricultural University Press, Warsaw, Poland.

Banasik, K., Skibiński, J. & Górski, D. (1995) Metody oceny erozji powierzchniowej i akumulacji rumowiska w zbiornikach. (Methods of estimation of erosion and reservoir sedimentation). In: *Metodyka zagospodarowania zasobów wodnych w małych zlewniach rzecznych* (Methodology of water resources management in a small river catchments), in Polish (ed. by A. Ciepielowski), 63–78 & 136–143. Warsaw Agricultural University Press, Warsaw, Poland.

Boardman, J. (2006) Soil erosion science: Reflections on the limitations of current approaches. *Catena* 68, 73–86.

Brański, J. & Banasik, K. (1996) Sediment yields and denudation rates in Poland. In: *Erosion and Sediment Yield: Global and Regional Perspectives* (ed. by D. E. Walling & B. Webb) (Proc. Exeter Symp.), 133–138. IAHS Publ. 236. IAHS Press, Wallingford, UK.

Dugga, K. N. & Soni, J. P. (2005) *Elements of Water Resources Engineering*. New Age Internatioanal Ltd, New Delhi.

Hejduk, L. (2001) Transport rumowiska i fosforu w zlewni rzeki Zagożdżonki (Sediment and phosphorus transport in a small river of Zagozdzonka). PhD Thesis, SGGW, Warsaw, Poland.

Horowitz, A. J. & Walling, D. E. (eds) (2005) *Sediment Budget II*. IAHS Publ. 292. IAHS Press, Wallingford, UK.

Kinnell, P. I. A. (2008) Sediment delivery from hillslopes and the Universal Soil Loss Equation: some perceptions and misconceptions. *Hydrol. Processes* 22, 3168–3175.

Meyer-Peter, E. & Mueller, R. (1948) Eine Formel zur Berechnung des Geschiebetriebes (A formula to estimate bed load intensity). *Schweizerische Bauzeitung* 67, 29-32.

Morris, G. L., Annandale, G. & Hotchkiss, R. (2007) Reservoir sedimentation. In: *Sedimentation Engineering – Processes, Measurements, Modeling and Practice* (ed. by M. H. Garcia). ASCE Manuals and Reports on Engineering Practice, no. 110, Reston, Virginia.

Morris, G. L. & Fan, J. (1998) *Reservoir Sedimentation Handbook*. McGraw-Hill Book Co., New York, 784.

Parsons, A. J. (2012) How useful are catchment sediment budgets? *Progress in Physical Geography* 36, 60–71.

Peng, G. (2008) Understanding watershed suspended sediment transport. *Progress in Physical Geography* 32, 243–263.

Popek, Z. (2006) *Warunki ruchu rumowiska wleczoneg w małej rzece nizinnej* (Bed load transport conditions in a small lowland river). Treatises and Monographs, no. 300. Warsaw University of Life Scieneces Press, Warsaw, Poland.

Roehl, I. W. (1962) Sediment source area, delivery ratios and influencing morphological factors.In: IAHS Publ. 59, 202–213.

Sadeghi, S. H. R., Mizuyama, T., Miyata, S., Gomi, T., Kosugi, K., Fukushima, T., Mizugaki, S. & Onda, Y. (2008) Determinant factors of sediment graphs and rating loops in a reforested watershed. *J. Hydrology* 356, 271–282.

Skibiński, J. (1976) Próba ilościowej oceny intensywności transportu rumowiska wleczonego w rzekach środkowej Polski (An attempt of estimation of bed load transport intensity in rivers of middle Poland). Treatises and Monographs, no. 74. Warsaw Agricultural University Press, Warsaw, Poland.

Strand, R. I. & Pemberton, E. L. (1982) *Reservoir Sedimentation, Technical Guidelines for Bureau of Reclamation*. US Department of the Interior, Denver, Colorado.

Walling, D. E. & Collins, A. L. (2008) The catchment sediment budget as a management tool. *Environmental Science & Policy* 11, 136–143.

Wischmeier, W. H. & Smith, D. D. (1978) *Predicting rainfall erosion losses – A guide to conservation planning*. Agricultural Handbook, no. 537. Washington DC, USDA-ARS.

Wiśniewski, B. (1969) Zamulanie zbiorników w Polsce oraz próba jego prognozy na podstawie instensywności denudacji (Siltation of reservoirs in Poland and an attempt of prediction on the base of denudation intensity). *Archiwum Hydrotechniki* 16, 481–504.