Variations in suspended sediment grain sizes in flood events of a small lowland river

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Abstract The grain size of suspended sediment and its variation during river flows is important information required for the modelling of river sediment transport and reservoir siltation, as well as for understanding the role of sediment particles in a variety of environmental processes. In this study, the results of grain size analyses of suspended sediment transported during flood events in a small lowland river are presented. The investigated area is the agricultural catchment of the River Zagozdzonka, a tributary of the River Vistula, located in the centre of Poland, approx. 100 km south of Warsaw. A total of 160 suspended sediment samples were collected in the period 2004–2007 during 11 flood events, caused by rainfall, snowmelt or a combination of both, and the samples were analysed for their particle size distribution. Mean values of the d_{50} of the suspended sediment for the events varied from 48 μm to 98 μm, and there was a tendency for an increase in particle size with increasing discharge.

Key words suspended sediment; grain size distribution; discharge-grain size relation

INTRODUCTION

The grain size of suspended sediment and its variation in river flows is important information required for the modelling of river sediment transport and reservoir siltation, as well as for understanding the role of sediment particles in a variety of environmental processes (Green *et al*., 1978; Slattery & Burt, 1998; Walling *et al*., 2000; Banasik *et al*., 2005; Banasik & Mitchell, 2008). The transport of sediments, both in suspended and bed load form, is one of the key processes which control river morphology. The size of the transported particles can be a factor in distinguishing between suspended load and bed load (Morris & Fan, 1997). Some authors give quite precise information about particle size and they connect it with the mode of sediment transport, i.e. that smaller (i.e. <0.05 mm) and lighter particles (including organic material) are typically transported in suspension in flowing water, while heavier particles (i.e. in the range of 0.1–100 mm) are transported as bed load, often rolling or bouncing along the channel bed. However, the border between suspended material and bed load material is very dynamic and mainly depends on water velocity. This is more important during flood events, when the velocity and discharge change the rate and mode of sediment transport very quickly. Generally, it is difficult to find relationships between discharge and particle size, especially in small lowland rivers, as the relationship can be completely different, even in quite similar catchments (Walling & Moorehead, 1989). In cases where there was no clear relation (e.g. Bogen, 1992; Stone & Walling, 1997), the authors suggest that the variation in particle size is related more to variations in sediment supply than to variations in sediment transport capacity. Lenzi & Marchi (2000) reported the increase of coarser suspended material near the peak flow during large floods in a mountain stream. Sometimes the coarser particles have been found on the rising limb of the hydrograph during large floods (Walling *et al.*, 2000), although a decrease of sediment size with an increase in flow has also been reported (Slattery & Burt, 1998). The grain size–discharge relationship can also be dependent on low-flow and high-flow seasons. For example, Xu (1999) reported coarser suspended particles during low-flow and finer particles during high-flow conditions. Differences between suspended sediment grain sizes during flow events have also been reported for the Zagożdżonka River, Poland (Banasik & Hejduk, 2005). Based on time-integrated sediment samples collected over 2 years, Hejduk *et al.* (2006) found a slight increase in mean particle diameter (d_{50}) with increasing average discharge.

STUDY AREA AND METHODS

Location and characteristics of the catchment

The Zagozdzonka catchment (Fig. 1) is a small agricultural, lowland catchment, located in central Poland, about 100 km south of Warsaw. Hydrological field investigations of the Zagozdzonka River, at Plachty, have been carried out by the Department of Water Engineering and Environmental Restoration of Warsaw University of Life Science since 1962. Monitoring of river flow at the Czarna gauging station, located upstream of Plachty, started in 1980. Since 1991 the investigation has been intensified and the river gauging station at Czarna has been equipped with automatic recorders of rainfall and water level, and with instruments to measure water quality parameters, such as temperature, turbidity and sediment transport. In 2005, an electronic system of data recording, logging and transmitting was installed. The catchment area is 82.4 km^2 at the Plachty gauging station, whereas the subcatchment area at Czarna is 23.4 km^2.

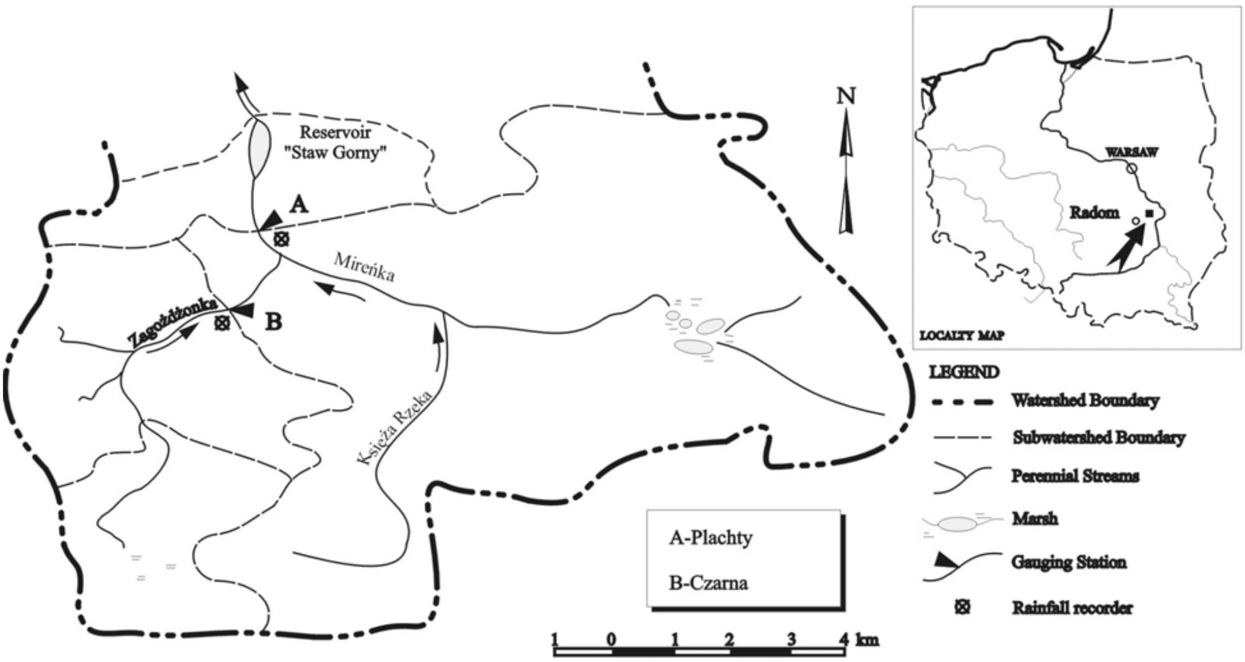

Fig. 1 Location map of the Zagozdzonka catchment and gauging stations.

Rainfall and runoff

The mean annual precipitation and runoff for the period 1963–2008 are estimated at 606 mm and 107 mm, respectively, based on data collected by the Department of Water Engineering and Environmental Restoration of Warsaw University of Life Sciences at Plachty, and data (1963–1982) from available publications of the Polish hydro-meteorological service (IMiGW) for the nearest raingauge, 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. Maximum annual runoff of 209 mm was measured in 1980, and the minimum of 52 mm was measured in 1992. Annual runoff coefficients (ratio of runoff to precipitation) for the area to the Plachty gauging station range from 0.088 (1992) to 0.320 (1979), with a mean value of 0.177. The mean annual suspended sediment concentration (SSC) is relatively low and estimated at 14 mg L^{-1}. However, during floods the SSC increases and the maximum recorded value was 220 mg L^{-1} (Hejduk, 2001)

Topography, land use and soils

The lowland, Zagożdżonka catchment, has a typical topography for this part of Poland. Absolute relief is 26.5 m in the subcatchment (upstream of B, Fig. 1), and 34 m for the entire catchment (upstream of A, Fig. 1). The mean slopes of the main channels range from 2.5 to 3.5 m per 1000 m. Local depressions, which do not contribute to direct runoff and sediment yield from the catchment, constitute a significant part of the area (i.e. 3.8 km^2 and 19.8 km^2 upstream of the Czarna and Plachty gauging stations, respectively). Land use is dominated by arable land (small grain and potatoes), which occupies about 70% of the catchment, and about 20% is covered by forest and 10% is pasture (Banasik, 1994). Sandy soils are dominant in the watershed area (loamy sand, 50.5%; light loamy sand, 40.2%; and organic soils, 9.3%).

Discharge measurement and sample collection

River flow at the Czarna gauging station has been estimated based on continuous water level records and on a hydraulic rating curve for a sharp-crested weir (Figs 2 and 3), which was checked using hydrometric current meter measurements.

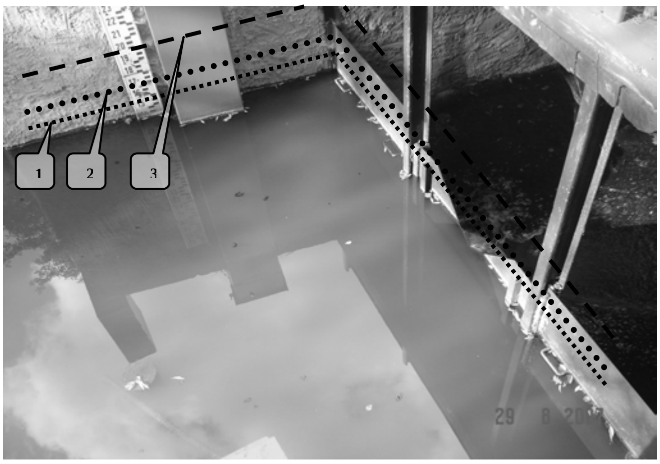

Fig. 2 Upstream view of the sharp-crested weir of the gauging station at Czarna (the notation 1 indicates the water level at mean discharge, 2 is the water level above which the samples for suspended sediment analysis were taken, and 3 is the water level corresponding to the 2-year flood).

Fig. 3 View of the stream gauging station at Czarna (photo is looking upstream and was taken at a discharge, which is close to the 2-year flood).

Samples of river water during high-flow events were collected using an American Sigma Streamline 800 SL automatic sampler installed at the Czarna gauging station. The sampler collects up to 24 1-L samples with a programmable time step (Górski & Hejduk 1998; Górski *et al.*, 2000). Samples were taken at a fixed intake nozzle, positioned under the water surface at a height of approx. 0.5 m above the channel bed and approx. 3 m upstream of the weir. The sampler was installed on an unused mill weir structure (Fig. 3), constructed in the 1950s (Banasik *et al.*, 1985).

To avoid sampling during low flow, the pump started collecting samples when the water stage at Czarna exceeded the level of the horizontal crest of the middle weir section (see Fig. 2). Discharge at this water level is close to 0.13 $m^3 s^{-1}$, which is about twice the mean annual discharge. During the flood events, the water samples were taken at 2-h time steps. The number of samples taken during an event was limited by sampler capacity (i.e. to 24 samples) and by flood duration, and was also limited by failure of the equipment. When the water level dropped below the level of the horizontal crest of the middle weir section (Fig. 2; e.g. below approx. 0.13 $m^3 s^{-1}$) sampling stopped until the water stage rose above the trigger threshold (i.e. next high-flow event), which ensures that samples were taken only from flood flows. During the study period, the capacity of the auto-sampler (i.e. 24 samples) was filled twice. In total, 160 samples were collected in the period 2004–2007 during 11 flood events, which were caused by rainfall, snowmelt or a combination of both.

Grain size distributions

After collection, the samples were stored in a refrigerator for a few days, and then taken to the laboratory for the determination of grain size distributions by laser diffraction using a Malvern Masteries Micro Plus. This instrument is suitable for measuring particles within the range 0.05 to 550 µm. The results from this method represent the equivalent diameters, assuming spheres of equal volume (Malvern, 1997). The samples were not treated with any special preparation (for example drying, removal of organic matter, addition of dispersant), which means that the samples represent the particle size distribution of sediment in the river at the time of collection. It should be noted, that the sampling equipment used to collected water samples uses a pump to draw samples from the river to the collection bottles. Tests showed that this sampling method did not influence the particle size distribution of the collected samples. However, there is a possibility that samples may have undergone some disaggregation or aggregation between collection and analysis.

RESULTS AND DISCUSSION

General characteristics of the 11 sampled events during the period 2004–2007 are presented in Table 1. Typically, between two and three high-flow events were sampled each year.

For this region of Poland, floods occur during spring and summer and are caused by snowmelt, rainfall or a combination of both. Seven of the 11 floods occurred during snowmelt periods (Table 2).

Table 1 Characteristics of the 11 measured high-flow events and the event mean suspended sediment (SS) particle diameter.

Category	Value average/event	Range
Rainfall depth, *P* (mm)	4.9	1.9–43.8
Rainfall + snowmelt depth (mm)	33.2	7.0–74.8
Runoff, *H* (mm)	4.91	0.66–22.9
Direct runoff, H_D (mm)	3.45	0.20–19.3
Peak discharge, Q_{max} ($m^3 s^{-1}$)	0.68	0.17–3.35
$Q_{max}/WQ_{50\%}$	0.65	0.16–3.22
Number of samples from event	14.5	6–24
Event mean diameter of SS, d_{50} (µm)	69.5	47.9–98.3

$WQ_{50\%}$: two-year-flood discharge = 1.04 $m^3 s^{-1}$.

Table 2 Characteristics of the measured flood events and information on the particle size distribution of the suspended sediment samples.

Date	Type of event	No. of samples	Q_{max} (m^3s^{-1})	d_{10} (µm)	SDd_{10} (µm)	d_{50} (µm)	SDd_{50} (µm)	d_{90} (µm)	SDd_{90} (µm)
2–3 February 2004	R&S	10	0.180	12.4	1.60	62.5	7.02	219	92.6
13–14 March 2004	S	8	0.206	9.91	4.10	49.8	12.8	165	55.3
21–22 March 2004	R	16	0.590	10.2	2.01	53.5	6.24	197	29.5
24–26 February 2005	R&S	11	0.195	19.1	3.90	98.3	26.0	298	66.3
16–18 March 2005	R&S	19	3.350	21.0	5.32	95.5	22.7	294	50.0
4–6 May 2005	R	24	0.898	21.1	5.57	88.7	21.1	298	43.5
26–27 March 2006	R&S	10	0.328	18.0	3.22	67.9	6.09	200	37.2
6–7 April 2006	R	24	0.382	21.5	5.44	79.3	17.1	264	40.5
31 August 2006	R	6	0.167	13.1	2.79	47.9	12.2	160	23.5
1–2 February 2007	R&S	23	0.903	17.2	4.71	69.0	16.9	224	50.4
24–25 March 2007	R&S	9	0.235	9.81	3.69	52.5	22.1	171	91.1
Average	–	14.5	0.676	15.7	3.85	69.5	15.5	226	52.7

R is for rainfall and S is for snowmelt events; Q_{max} is event peak discharge; d_{10}, d_{50} and d_{90} are the mean values of diameters of SS particles; SDd_{10}, SDd_{50} and SDd_{90} are the standard deviations of the diameters.

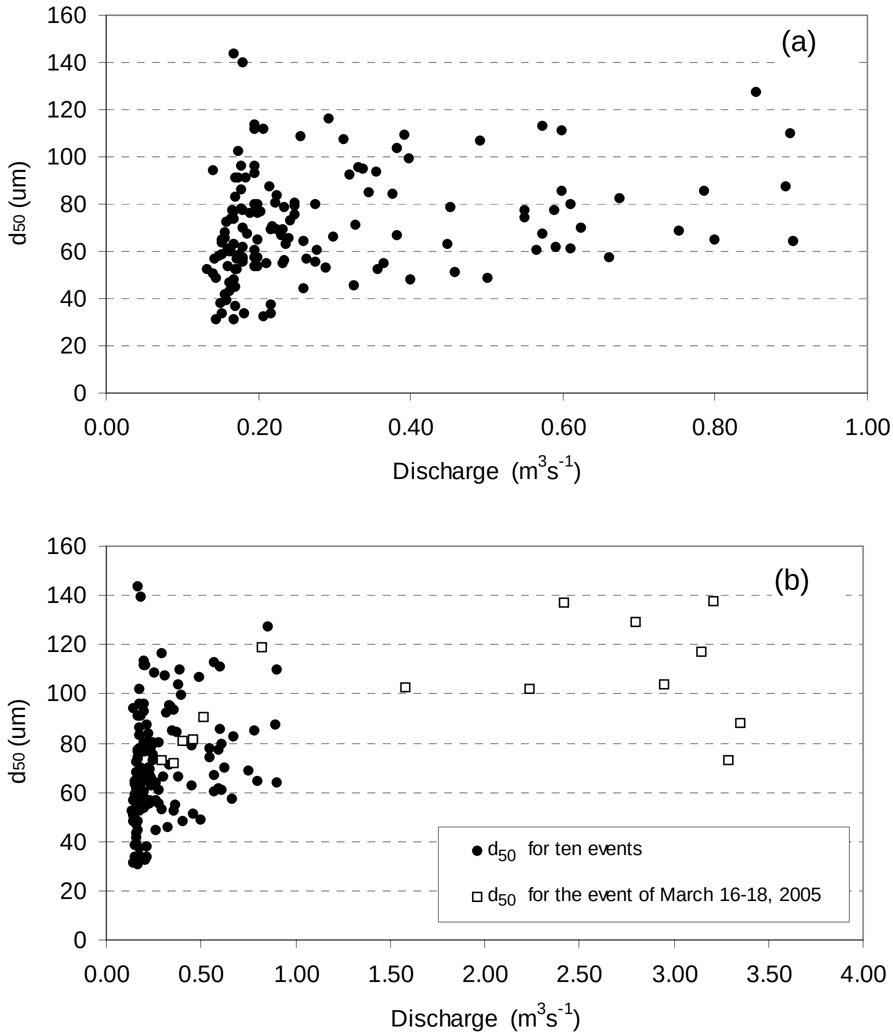

Fig. 4 Relation between d_{50} and discharge for suspended sediment samples collected during: (a) 10 events (without the highest flood event), and (b) all 11 events.

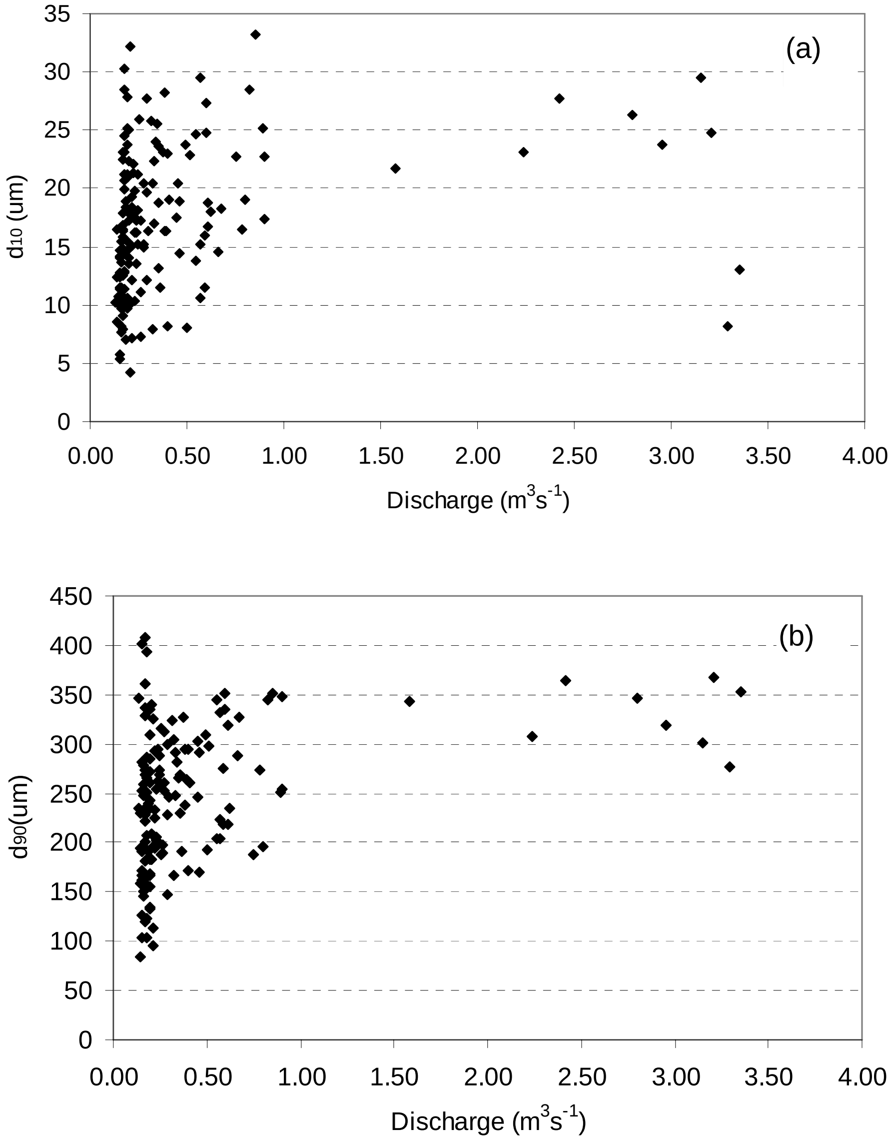

Fig. 5 Relation between particle diameter and discharge: (a) d_{10}; and (b) d_{90}

The particle diameters at the 10th, 50th and 90th percentiles (i.e. d_{10}, d_{50} and d_{90}) for all 160 samples are plotted against discharge at the time when the samples were taken in Figs 4 and 5. The data plotted in Figs 4 and 5 have a large variability at any given discharge. The arithmetic mean values and standard deviations of the diameters for the 11 events are given in Table 2. The event-average values for d_{10}, d_{50} and d_{90} are 15.7, 69.5 and 226 µm, respectively. The standard deviation of the values indicates the high variability of particle diameters within particular flood events.

There was no significant ($p > 0.05$) relation between "characteristic" (see Chanson, 2007) particle diameter and discharge for all samples ($r^2 < 0.02$, n = 160). The high variability of particle diameter was observed during both low and high discharges (Fig. 4). When the highest flood (which had a peak flow approx. 8 times higher than the average value of the other peak flows) was removed from the data set (Fig. 4(a)), the variation in particle d_{50} for discharge within the range of 0.2–0.9 $m^3 s^{-1}$ was similar to that for all events (Fig. 4(b)). Similar relations exist between discharge and the d_{10} and d_{90} (Fig. 5). One explanation is that the discharges during floods were not high enough to move the coarser particles. However, the source of the sediment can play an important role in controlling particle size. Most of the events were during the spring, after winter floods, but were not necessarily snowmelt floods. After winter, when the frozen soil thaws, the top soil particles are often poorly bound, both together and with the underlying ground surface, resulting in a greater diversity of particles with different sizes. There were no significant differences in sediment particle size between typical rain events and snowmelt or snowmelt–rainfall events, although this is partly a function of the limited number of samples collected for each event type; more data are required to examine this further.

Although there are no significant relations between discharge and particle size, there is a trend of an increase in the lowest values of particle size with increasing discharge. For example, from Fig. 4(b) it can be seen that for discharges in the range of 0.13–0.30 $m^3 s^{-1}$ the d_{50} is typically in the range of 30–120 µm, whereas for discharges of 0.30–1.00 $m^3 s^{-1}$ the range of d_{50} is 50–120 µm, and for discharges >1.0 $m^3 s^{-1}$ the range of d_{50} is typically 70–140 µm. Hence, there is a slight increase of particle size with increase of discharge. The plots of d_{10} and d_{90} (Fig. 5) show a similar trend. Plotting the arithmetic mean values of d_{50} for the analysed events (given in Table 2), *versus* the peak discharges (Fig. 6, r^2 = 0.28), confirms the previous assertion that the particle size of suspended sediment transported during flood events increases with increasing discharge.

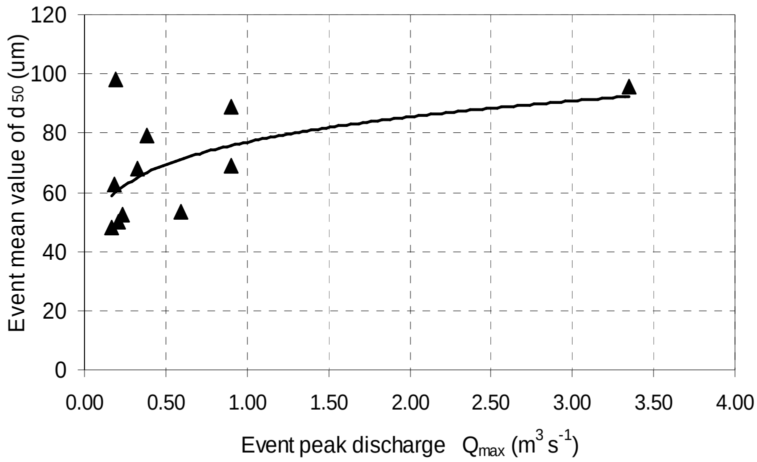

Fig. 6 Relation between event mean d_{50} and event peak discharge.

CONCLUSION

The grain size of suspended sediment shows high variability during and between flood events. Based on 11 flood events, the event-average d_{10}, d_{50} and d_{90} for this small lowland catchment are 15.7 µm, 69.5 µm and 226 µm, respectively. For a certain particle size diameter (i.e. d_{50}, d_{90}), there is a wide range in values (e.g. approx. 30–150 µm for d_{50}), although the range is fairly constant across discharges, even for high-flow events. Mean values of d_{50} for the analysed events varied from 48 µm to 98 µm, and minimum values tended to increase with an increase in event peak discharge.

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REFERENCES

Banasik, K. (1994) Model sedymentogramu wezbrania opadowego w malej zlewni rolniczej (Sedimentgraph model of rainfall event in a small agricultural watershed). Theses & Monographs of Warsaw Agricultural University-SGGW, Warsaw, Poland (in Polish with an English summary).

Banasik, K. & Hejduk, L. (2005) Badania granulometrii rumowiska unoszonego w małej zlewni nizinnej (Investigation on granulometry of suspended sediment in a small lowland river). *Acta Agrophisica* **5**, 253–262.

Banasik, K. & Mitchell J. K. (2008) Conceptual model of sedimentgraph from flood events in small agricultural watershed. *Annals of Warsaw University of Life Sciences - SGGW, Land Reclamation* **39**, 49–57 (http://ann_landreclam.sggw.pl/z39/art4.pdf).

Banasik, K., Byczkowski, A. & Kubrak, J.(1985) Wykorzystanie malych budowli wodnych do pomiaru natezenia przeplywu (Utility of small hydraulic structures for estimating river discharge). Studia i Materialy Oceanologiczne. *Komitet Badan Morza PAN, Gdansk* **47**, 189–204.

Banasik, K., Hejduk, L. & Popek, Z. (2005) Sediment problems of small river catchments and reservoirs in Poland. In: *Computational Modeling for the Development of Sustainable Water-Resources Systems in Poland* (ed. by M. S. Altinakar, W. Czernuszenko, P. M. Rowiński & S. S. J. Wang), 179–207. Publications of the Institute of Geophysics, Polish Academy of Sciences, E-5 (387).

Bogen, J. (1992) Monitoring grain size of suspended sediment in rivers. In: *Erosion and Sediment Transport Monitoring Programmes in River Basins* (ed. by J. Bogen, D. E. Walling & T. J. Day), 183–190. IAHS Publ. 210. IAHS Press, Wallingford, UK.

Chanson, H. (2007) *The Hydraulics of Open Channel Flow: An Introduction*. Elsevier, Amsterdam, The Netherlands.

Green, D. B., Logan T. J. & Smeck N. E. (1978) Phosphate adsorption-desorption characteristics of suspended sediment in the Maumee river basin of Ohio. *J. Environ Qual.* **7**, 208–212.

Górski, D. & Hejduk, L. (1998) Stanowisko pomiarowe do badań nad ilością i jakością odpływu z małej zlewni rolniczej (River gauging station for monitoring the quantity and quality of runoff from a small agricultural catchment). *Przegląd Naukowy Wydziału Inżynierii i Kształtowania Środowiska* **15**, 288–296.

Górski, D., Hejduk, L. & Banasik, K. (2000) Nowe metody pomiarowe rumowiska unoszonego (New methods for monitoring the suspended sediment). *Przegląd Naukowy Wydziału Inżynierii i Kształtowania Środowiska* **18**, 69–80.

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.

Hejduk, L., Hejduk, A. & Banasik, K. (2006) Suspended sediment transport during rainfall and snowmelt-rainfall floods in a small lowland catchment, central Poland. In: *Soil Erosion and Sediment Redistribution in River Catchments* (ed. by P. N. Owens & A. J. Collins), 94–100. CABI Publishing, Wallingford, UK.

Lenzi, A. M. & Marchi, L. (2000) Suspended sediment load during floods in a small stream of the Dolomites (northeastern Italy). *Catena* **39**, 267–182.

Malvern (1997) *Getting Started*. Malvern Instruments Ltd, UK.

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

Slattery, M. C. & Burt, T. P. (1998) Particle size characteristics of suspended sediment in hillslope runoff and stream flow. *Earth Surf. Processes Landf.* **22**, 705–719.

Stone, P. M. & Walling, D. E. (1997) Particle size selectivity considerations in suspended sediment budget investigations. *Water, Air Soil Pollut.* **99**, 63–70.

Walling, D. E. & Moorehead, P. W. (1989) The particle size characteristics of fluvial suspended sediment: an overview. *Hydrobiologia* **176/177**, 125–149.

Walling, D. E., Owens, P. N., Waterfall, B. D., Leeks, G. J. L. & Wass, P. D. (2000) The particle size characteristics of fluvial suspended sediment in the Humber and Tweed catchments, UK. *Sci. Total Environ.* **251/252**, 205–222.

WMO (1994) *Guide for Hydrological Practices.* WMO no. 168.

Xu, J. (1999) Grain-size characteristics of suspended sediment in the Yellow River, China. *Catena* **38**, 243–263.