Sediment Dynamics and the Hydromorphology of Fluvial Systems (Proceedings of a symposium held in Dundee, UK, July 2006). IAHS Publ. 306, 2006.

Importance of watershed lag times in IUSG development

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Abstract Sedimentgraphs (graphs of suspended sediment load associated with hydrographs caused by rainfall) are essential for sediment yield assessments, for providing input data for prediction models of sediment deposition in reservoirs, for designing efficient sediment control structures, and for water quality predictions. An important part in the procedure of sedimentgraph prediction is the instantaneous unit sedimentgraph (IUSG) estimation. The IUSG used in this study has been developed by using the concepts of the instantaneous unit hydrograph (IUH) and the dimensionless sediment concentration distribution (DSCD). A procedure for estimating the sediment routing coefficient, which is a key parameter of the IUSG, based on measured rainfall–runoff-suspended sediment data (i.e. based on lag times), is applied. Also the relationships between IUSG and IUH characteristics (i.e. graph-peak values and times to peaks) are given. Field data from a small agricultural watershed in central Poland were used to demonstrate the relationship between lag times. The analysis shows that: (a) lag times are essential in estimating the parameters of IUSG; (b) a significant linear relationship exists between the lag time for hydrographs LAG and lag time of the sedimentgraphs LAG_s; (c) the values of LAG_s/LAG are for most cases smaller than 1 and decrease with the rainfall depth increase.

Key words lag time; sedimentgraph; small watershed; suspended sediment; wash load

INTRODUCTION

Estimates of sedimentgraphs (graphs of suspended sediment load associated with hydrographs caused by rainfall) are essential for sediment yield assessment, providing input data for prediction models of sediment deposition in reservoirs, designing efficient sediment control structures, and for water quality predictions. The idea of the sedimentgraph model, introduced by Williams (1978), was used in a previous investigation (Banasik & Woodward, 1992; Banasik & Blay, 1994) for predicting and regenerating the suspended sediment load as a response of a small catchment to heavy rainfall. A new definition of the instantaneous unit sedimentgraph (IUSG) was later developed (Banasik, 1994, 1995; Banasik & Walling, 1996). The IUSG has been incorporated into the sedimentgraph model (SEGMO), based on a lumped parametric approach.

The sedimentgraph model, which was developed for predicting watershed response to heavy rainfall, consists of two parts; a hydrological sub-model and sedimentology sub-model. The hydrological submodel uses the Soil Conservation

Service CN method (DVWK, 1984; SCS, 1986; Ignar & Banasik, 1994) to estimate effective rainfall, and the instantaneous unit hydrograph (IUH) procedure to transform the effective rainfall into a direct runoff hydrograph. The sedimentology submodel uses a form of the modified Universal Soil Loss Equation to estimate the amount of suspended sediment produced during the rainfall–runoff event and the instantaneous unit sedimentgraph (IUSG) procedure to transform the produced sediment into sedimentgraph.

DESCRIPTION OF IUSG PROCEDURE AND PARAMETERS

The IUSG is defined as the time distribution of sediment generated from an instantaneous burst of rainfall producing one unit of sediment. The IUSG presented here is based on the IUH developed by Nash (1957) i.e.:

$$u(t) = \frac{1}{k \cdot \Gamma(N)} \cdot (t/k)^{N-1} \cdot \exp(-t/k) \tag{1}$$

and the first-order kinetic equation written in dimensionless form and termed the dimensionless sediment concentration distribution (DSCD):

$$c(t) = \exp(-B \cdot t) \tag{2}$$

where $u(t)$ are the ordinates of the IUH (1/hour), N and k are the Nash model parameters: N is number of reservoirs (–), k is the retention time of reservoir (hours), $\Gamma(N)$ is gamma function, $c(t)$ are the ordinates of the DSCD (–), B is sediment routing coefficient (1/hour), and t is time (hours).

The IUSG is calculated by the formula:

$$s(t) = \frac{u(t) \cdot c(t)}{\int_0^\infty u(t) \cdot c(t)\, \mathrm{d}t} \tag{3}$$

which, after inserting equations (1) and (2), produces the following formula (Banasik, 1994):

$$s(t) = \frac{B \cdot k + 1}{k \cdot \Gamma(N)} \cdot [t(B + 1/k)]^{N-1} \cdot \exp[-t(B + 1/k)] \qquad \text{for } B \geq -1/k \tag{4}$$

where $s(t)$ are the IUSG ordinates (1/hour). The IUSG has three parameters N and k which are also IUH parameters and a third parameter B, the sediment routing coefficient.

The characteristic values of the IUSG (i.e. time to peak) can be calculated from the formula:

$$t_{ps} = \frac{(N-1) \cdot k}{1 + B \cdot k} \tag{5}$$

and the maximum ordinate of IUSG can be computed from the equation:

$$s_p = \frac{1 + B \cdot k}{k \cdot \Gamma(N)} \cdot \frac{(N-1)^{N\text{-}1}}{\exp(N-1)} \tag{6}$$

where t_{ps} is the time to peak of IUSG (hour), and s_p is the maximum ordinate of IUSG (1/hour).

As the respective values for IUH are calculated from the equations:

$$t_p = (N-1) \cdot k \tag{7}$$

and:

$$u_p = \frac{1}{k \cdot \Gamma(N)} \cdot \frac{(N-1)^{N\text{-}1}}{\exp(N-1)} \tag{8}$$

where t_p is time to peak of IUH (hour), and u_p is the maximum ordinate of IUH (1/hour), so the ratio of the characteristic values of IUSG and IUH can be computed from the formulae:

$$\frac{t_{ps}}{t_p} = \frac{1}{(1 + B \cdot k)} \tag{9}$$

and:

$$\frac{s_p}{u_p} = 1 + B \cdot k \tag{10}$$

It is clear that when *B* equals zero the characteristic values of IUH and IUSG are the same and the right side of equation (4) assumes the form of the IUH (equation (1)). It can also be found from equation (9), that for $B > 0$, the time to peak of the IUSG is shorter than the time to peak of the IUH, and the IUSG peak is higher than the IUH peak (equation (10)).

USE OF LAG TIMES IN ESTIMATION OF SEDIMENT ROUTING COEFFICIENT

One of the characteristic values in rainfall–runoff models is the retention of the system or the lag time, defined as the time elapsed between the centroids of the effective rainfall and the direct runoff hydrograph. For the IUH derived by Nash, the lag time is estimated using the formula:

$$LAG = N \cdot k \tag{11}$$

For the IUSG, the lag time (LAG_s) can be calculated using equation:

$$LAG_s = \frac{N \cdot k}{1 + B \cdot k} \tag{12}$$

Making use of equations (11) and (12), the routing coefficient *B* can be computed using the formula:

$$B = (LAG/LAG_s - 1)/k \tag{13}$$

Since LAG, LAG_s and k can be estimated from rainfall, runoff and suspended sediment data, the routing coefficient B, can be estimated using equation (13).

Inserting equation (13) into equations (9) and (10) one derives very useful formulae for the relationships between the characteristic values of the IUH and the IUSG. The ratios of lag times take the following forms:

$$\frac{t_{ps}}{t_p} = \frac{LAG_s}{LAG} \tag{14}$$

$$\frac{s_p}{u_p} = \frac{LAG}{LAG_s} \tag{15}$$

Equations (14) and (15) show the importance of hydrograph and sedimentgraph lag times in demonstrating how the IUSG characteristics can easily be derived from IUH characteristics.

Using measured data from rainfall–runoff events, the lag time can be calculated as:

$$LAG = M_{1Q} - M_{1P} \tag{16}$$

where M_{1Q} and M_{1P} are the first statistical moments of the direct runoff hydrograph and the effective rainfall hyetograph (h) (Fig. 1), respectively. Based on measured data, the lag time for the sedimentgraph (LAG_S) is defined as time elapsed between the centroids of the sediment production graph (similar to effective rainfall hyetograph) and the sedimentgraph, and can be computed from the formula:

$$LAG_S = M_{1S} - M_{1E} \tag{17}$$

where M_{1S} and M_{1E} are the first statistical moments of the graph of direct suspended sediment rate, and the graph of sediment production (h), respectively (Banasik *et al.* 2005). Data from a small agricultural watershed were analyzed to investigate the relationship between LAG_s and LAG.

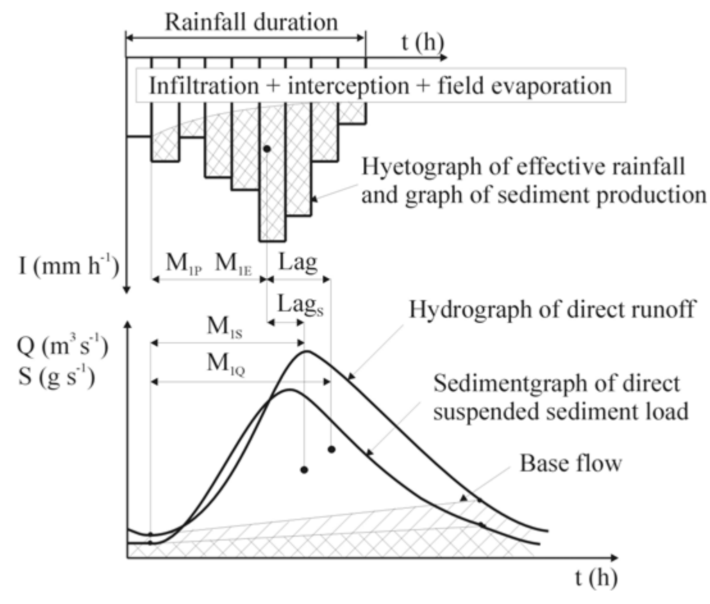

Fig. 1 Definition of lag times for runoff (LAG) and for suspended sediment yield (LAG_S).

DATA USED AND RESULTS

Rainfall, runoff and suspended sediment data from 15 events from the 23.4 km^2 lowland watershed of the upper part of Zagożdżonka River at the Czarna gauging station, collected by the Department of Water Engineering and Environmental Recultivation, Warsaw Agricultural University, in the period 1999–2003, have been used in the investigation. The location of the upper part of the Zagozdzonka River, which is a left tributary of Vistula River, is shown in Fig. 2. In this area the long-term mean annual precipitation is 610 mm and runoff 109 mm. Land use in the watershed upstream of the Czarna gauge is dominated by arable land and sandy soils are the dominant type in the area. The absolute relief of the watershed to the Czarna gauging station is 26.5 m and the mean slopes of the main channels are in the range 2.0–3.5‰. The gauging station at Czarna is equipped with automatic and electronic devices for measuring rainfall intensity (tipping bucket rainfall gauge), water level (water levels sensor) and turbidity (continuous recording infrared turbidity sensor). Estimates of the suspended sediment concentration were based on the relationship between turbidity at the measurement point and the suspended sediment concentrations in the river cross-section. The relationship was established by field calibration. The measured data have been recorded on a data logger using a time interval of 10 minutes.

The basic characteristics of the measured events and their respective lag times are given in Table 1. The rainfall depth *P* associated with the 15 events, measured at the gauging station of Czarna, varied from 3.0 to 60.9 mm, with an average of 18.6 mm. The effective rainfall depth *H* varied from 0.20 to 5.16 mm, with an average of 1.20 mm. The peak discharges Q_{max} have a range from 0.22 to 2.08 m^3 s^{-1}, with an average of 0.69 m^3 s^{-1}. An example of a measured hydrograph and sedimentgraph for the event of 22nd April 2001 at the gauge Czarna is shown in Fig. 3 with lag times for sediment yield vs lag time for runoff shown in Fig. 4. It can be observed from Fig. 4 that in most events the lag times of runoff hydrographs are longer than the lag

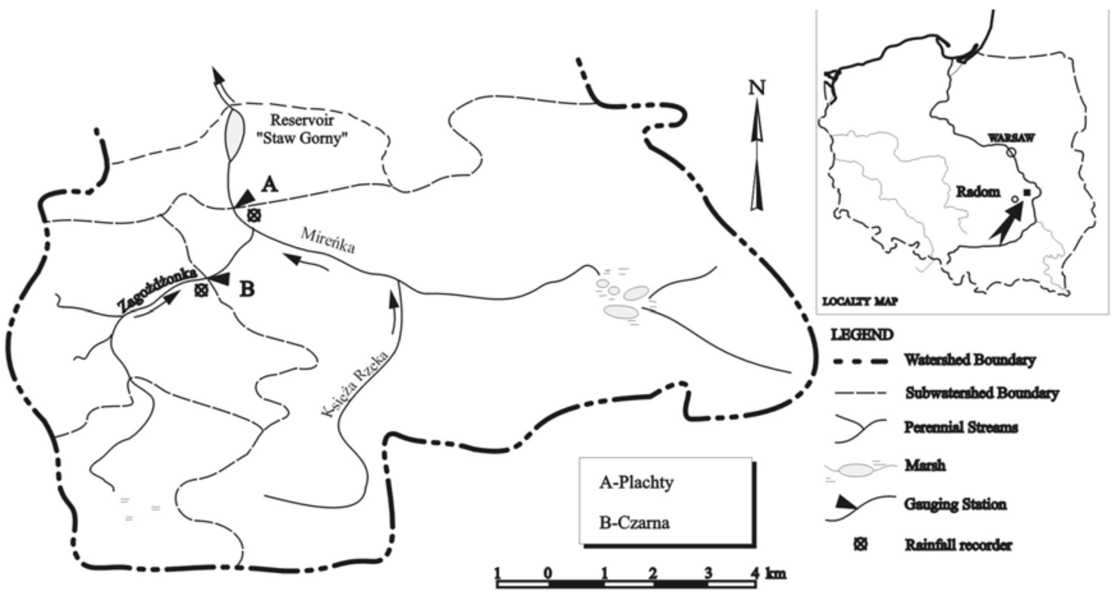

Fig. 2 Location map of the watershed.

Table 1 Characteristics of the measured events and their lag times.

Category	Unit	Value avg./event	Range
Rainfall depth, P_m	mm	18.6	3.0–60.9
Effective rainfall, H	mm	1.20	0.20–5.16
Peak discharge, Q_{max}	$m^3 s^{-1}$	0.69	0.22–2.08
$Q_{max}/WQ_{50\%}$	–	0.70	0.21–1.98
Peak concentration, c_{max}	mg dm^{-3}	47.4	16.9–213.0
LAG	hours	7.19	2.42–11.5
LAG_s	hours	6.56	1.63–10.2
LAG_s/LAG	–	0.90	0.67–1.11

$WQ_{50\%}$, two-year-flood discharge.

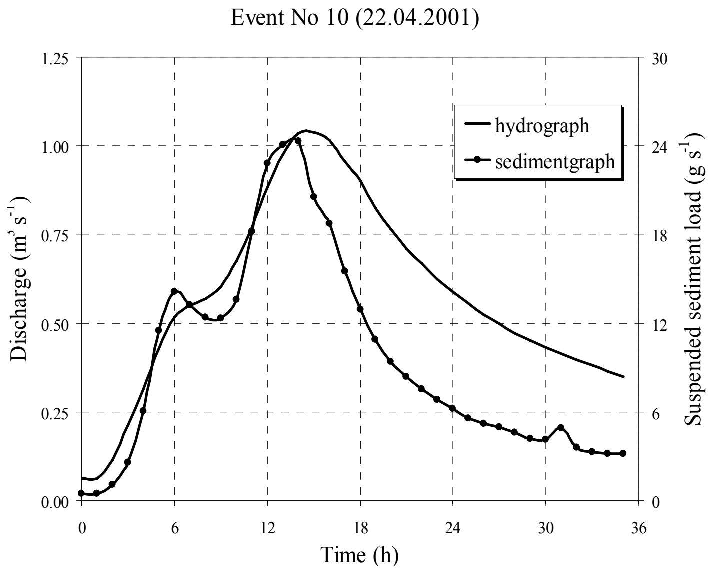

Fig. 3 Runoff hydrograph and sedimentgraph of the event of 22 April 2001.

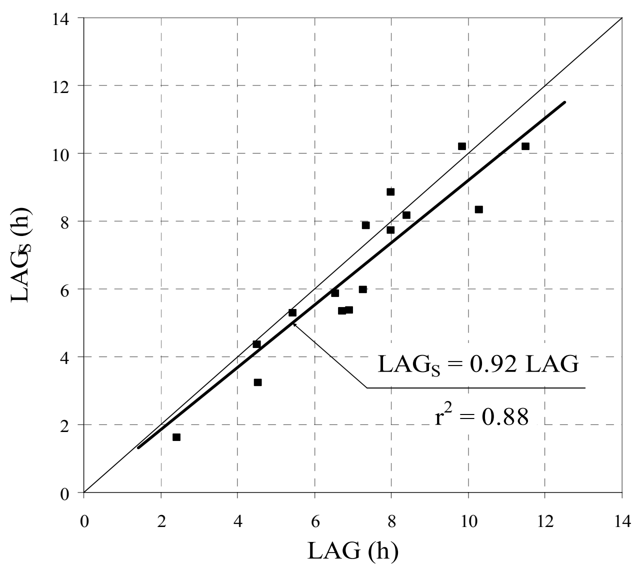

Fig. 4 Comparison of measured lag times for runoff hydrograph (*LAG*) and sedimentgraph (LAG_s).

times of sedimentgraphs (for 12 out the 15 events). The lag times of runoff hydrographs varied from 2.42 h to 11.5 h, with an average of 7.19 h, while the lag times of sedimentgraphs varied from 1.63 h to 10.2 h, with an average of 6.56 h. The ratio of lag times (i.e. LAG_s/LAG) computed for each of the events varies from 0.67 to 1.11, with a mean of 0.90, and a sample standard deviation of 0.12. The lag time data shown in Fig. 4 have enabled the following regression relationships to be derived:

$$LAG_s = 0.92 \cdot LAG \tag{18}$$

with a coefficient of determination of 0.88.

The ratio LAG_s/LAG of the recorded events also indicates a tendency to decrease with rainfall depth (Fig. 5). The exponential formula which approximates the data shown in Fig. 5, and may be a preliminary estimate for the LAG_S/LAG ratio in small watersheds with similar characteristics, is written in the form:

$$LAG_s / LAG = 0.76 + 0.38 \cdot \exp(-P/11.8) \tag{19}$$

where P is rainfall depth in mm.

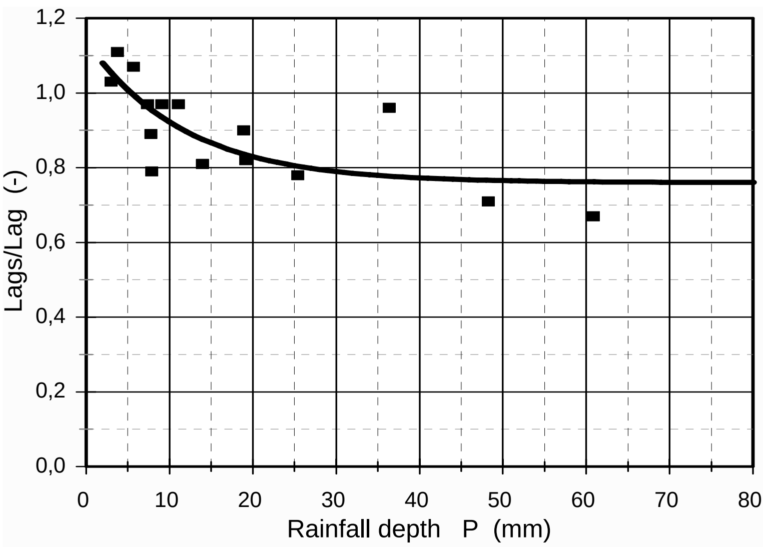

Fig. 5 Ratio LAG_s/LAG *vs* rainfall depth.

CONCLUSIONS

The description of the instantaneous unit sedimentgraph, IUSG, and analysis of rainfall–runoff–sediment-yield data presented here shows that:

(1) Lag times are essential in estimating the parameters and characteristics of the instantaneous unit sedimentgraph, IUSG.

(2) A significant linear relationship exists between the lag time for hydrographs, LAG, and lag time for the sedimentgraphs LAG_s.

(3) The values of LAG_s/LAG are for most of the recorded events smaller than 1, and decrease with the increase of rainfall depth.

Acknowledgements The study described in this paper has been carried out within research projects founded by the Ministry of Education and Science (KBN Project no. 4T09D031%25 and COST/21/2005). The support provided by this organization is gratefully acknowledged.

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