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ESTIMATION OF LAG TIMES OF RAINFALL EVENTS FOR THREE SMALL RIVER BASINS

Mariusz Barszcz[1], Kazimierz Banasik[1], Frank Tönsmann[2]
[1] Department of Water Engineering and Environmental Recultivation, Warsaw Agricultural University, Poland
[2] Department of Hydraulic and Water-Resources Engineering, University of Kassel, Germany

ABSTRACT

Lag time of runoff – Lag is one of the characteristic values in rainfall-runoff modeling and lag time of sediment yield – Lag_S is an important characteristic in the procedure of predicting the suspended sediment rate (sedimentgraph). The relationship between the lag times (Lag_S/Lag) is used for estimating sediment routing coefficient – B, which is a key parameter of the instantaneous unit sedimentgraph (IUSG). The IUSG formula is needed to transform the sediment produced during rainfall into sedimentgraph.

The relationship Lag_S/Lag was examined for a three small basins (two of which are located in Poland, and one in Germany). The ratio Lag_S/Lag, estimated for events from the investigated basins, has been in the range from 0.49 to 1.11. A statistical significant correlation has been found between the value of Lag_S/Lag and rainfall depth in one of the basins.

Key words: small basin, lag time, instantaneous unit sedimentgraph.

INTRODUCTION

One of the characteristic values in rainfall-runoff modeling is the time of response or lag time of runoff – Lag, which is defined as the time elapsed between the centroids of the effective rainfall hyetograph and the direct runoff hydrograph. The lag time is estimated using formula:

$$Lag = M_{1Q} - M_{1P} \tag{1}$$

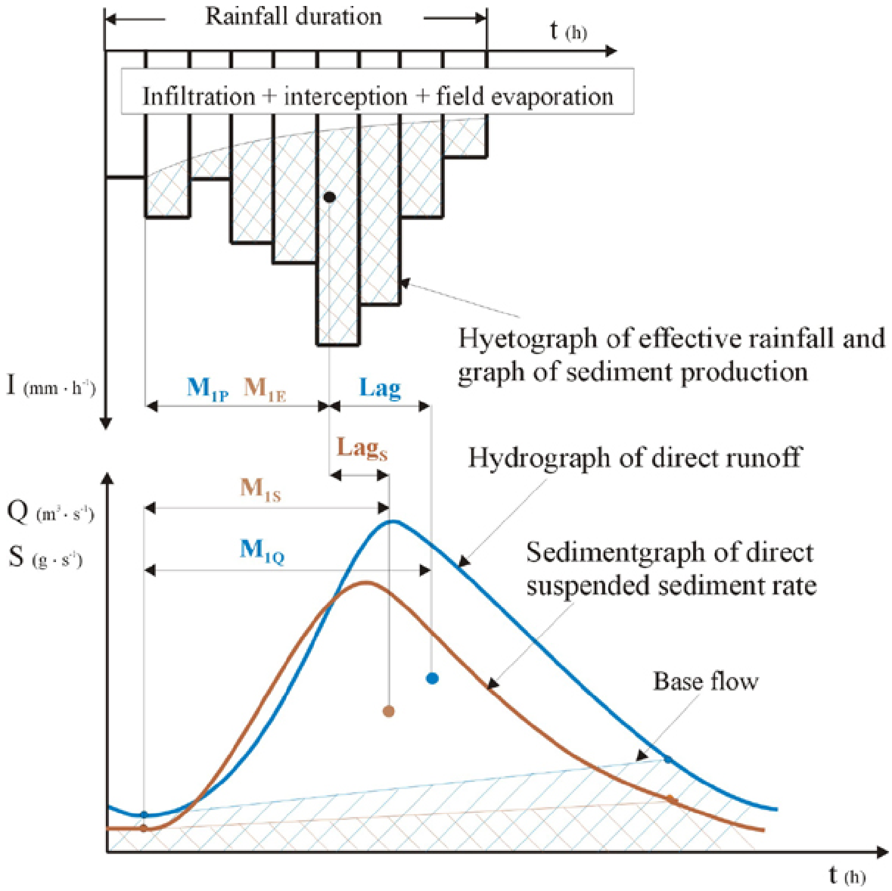
where M_{1Q} and M_{1P} are first statistical moments of the direct runoff hydrograph and the effective rainfall hyetograph (T), respectively.

An important characteristic in the process of predicting the time distribution of suspended sediment rate (sedimentgraph) is lag time of sediment yield – Lag_S, which is defined as time elapsed between centroids of sediment production graph (similar to effective rainfall hyetograph) and sedimentgraph (Fig. 1). Using recorded rainfall-runoff-suspended sediment rate data, the lag time for sedimentgraph could be computed from:

$$Lag_S = M_{1S} - M_{1E} \quad (2)$$

where M_{1S} and M_{1E} are first statistical moments of the graph of direct suspended sediment rate, and the graph of sediment production (T), respectively.

Fig. 1. Definition of lag times for runoff (Lag) and for suspended sediment yield (Lag_S)



The two lag times are needed for estimating the sediment routing coefficient – B of the instantaneous unit sedimentgraph – IUSG developed by Banasik [1]. The IUSG based on the instantaneous unit hydrograph – IUH and on a dimensionless sediment concentration distribution, and used for transforming the sediment produced during a specified rainfall duration into a sedimentgraph. For the IUH derived by Nash [6] the relationship between lag time of runoff and IUH parameters is expressed by:

$$Lag = N \cdot k \quad (3)$$

where N and k are the IUH parameters: N – number of reservoirs (–), k – retention parameter of the reservoirs (T). For the IUSG, the relationship is expressed by:

$$LAG_S = \frac{N \cdot k}{1 + B \cdot k} \quad (4)$$

The IUSG [1] has three parameters, two of which, N and k are also IUH parameters, and a third one, the sediment routing coefficient B (T^{-1}). Making use of equations (3) and (4), the sediment routing coefficient – B, which is needed to predict the shape of the IUSG, can be computed using:

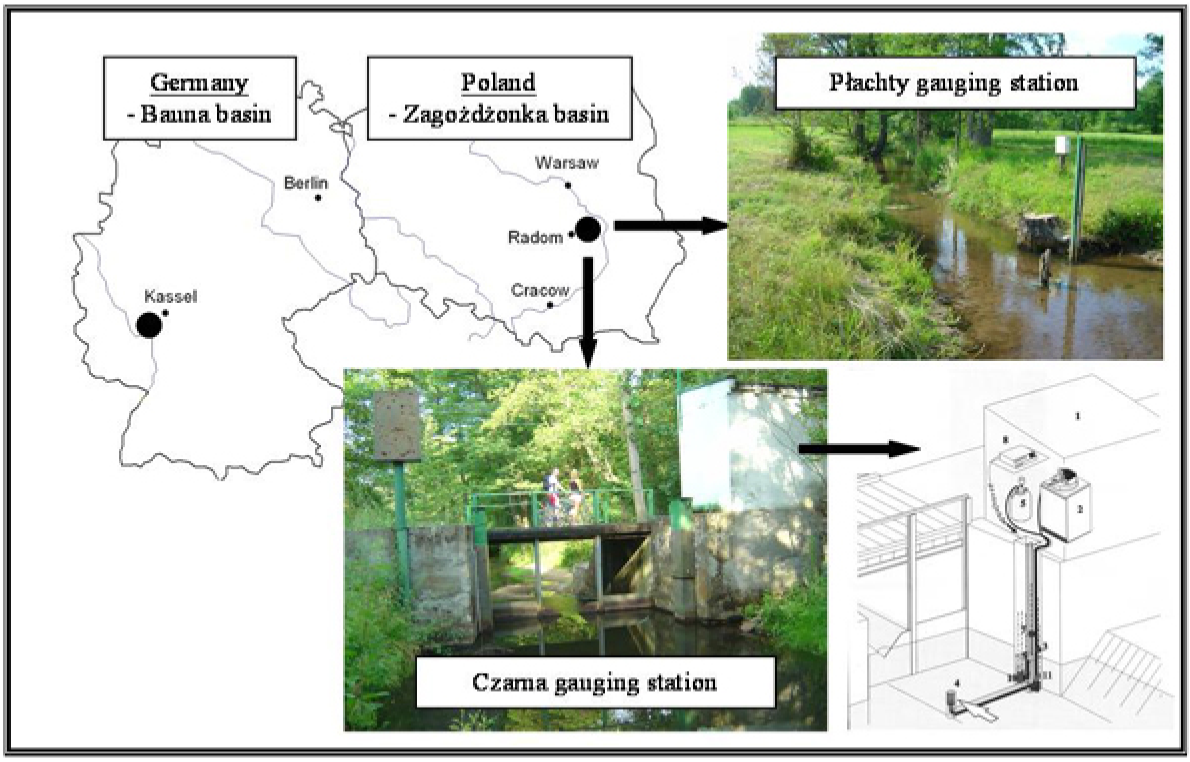
$$B = (Lag/Lag_S - 1)/k \quad (5)$$

The IUH parameters (N, k) are quite often investigated and are relatively easly to establish. To calculate the third one of the parameters of IUSG, i.e. the parameter B, the rainfall-runoff-suspended sediment rate data are needed. The key element of the parameter B calculation is the relationship between lag time of runoff – Lag and lag time of sediment – Lag_S. The first of them has been often analysed in hydrological investigations [2, 5, 7, 9]. There is however lack of investigation on Lag_S estimation as well as on relationship between Lag_S and Lag. The scope of the paper is present results of investigation on the relationships between Lag_S and Lag, carried out in three small river basins.

CHARACTERISTICS OF THE RIVER BASINS

The localization of the river basins is shows in Fig. 2. The Zagożdżonka river basin with the gauging station at Czarna and at Płachty is located in central of Poland (about 100 km south from Warsaw). The area of the basins at the gauging stations is 23.4 km^2 and 82.4 km^2, respectively. The Bauna river basin to the Kirchbauna gauging station is located in Germany in the southwest of Kassel.

Fig. 2. The Localization of the investigated basins



Land use in the lowland Zagożdżonka basin is dominated by arable land and sandy soils are the dominant type in the area. The absolute relief of the basin to Czarna and Płachty gauging station, where the Department of Water Engineering and Environment Recultivation, Warsaw Agricultural University conduct research is 26.5 m and 37 m, respectively. The river gauging station at Czarna is equipped with automatic and electronics devices, for measuring intensity of rainfall (using rainfall tiping bucket gauge), water level (water levels sensor) and turbidity (continuous recording turbidity infrared sensor). Estimation of suspended sediment concentration was based on relationship between turbidity at the measurement point and suspended sediment concentration in the river corss-section. The relationship was establish by field calibration. The measured data have been recorded on data logger RC-10 in time interval of the 10 minutes.

At Płachty gauging station water lewel and rainfall depth were continuously recorded using mechanical water level recorder and rain gauge recorder. Systematic suspended sediment sampling during a flood events, was carried out mannually for varying time intervals (depending on water level).

The Bauna basin with size of 45 km^2 to Kirchbauna gauging station is a typical small basin in low mountain range in Hesse, Germany. However, the proportions of the urbanized area and of the impervious surfaces are 24% and 11%, respectively, and are therefore relatively high. The rest of the basin consists of arable land (33%), wood lands (30%) and pastures (12%). The soils in the basin are of low permability [8]. The rainfall-runoff-suspended sediment data used in the investigations were collected by Department of Hydraulic Structures and Water Resources Engineering of the University of Kassel, within a study of flood control in the Bauna basin [11] and of forecasting the morphological modifications in the Bauna river [10].

DATA USED AND RESULTS

The relationship between Lag and Lag_S

All recorded events, with peak discharge at least two times larger then discharge at the beginning of the event, and which have the complete date on rainfall, runoff and suspended sediment discharge, have been selected for the investigations. There were 19, 4 and 10 events from the Czarna, Płachty and the Kirchbauna gauging stations, respectively. The main characteristics of the recorded and analysed rainfall-runoff-sediment yield events from the three gauging stations are presented in Table 1, 2 and 3.

Effective rainfall distribution during events have been estimated using the CN-SCS method [12], assuming that the effective rainfall depth is equal to direct runoff depth. Sediment production for each time interval of effective rainfall, which was needed for estimating lag time of sediment yield, was computed as a function of the incremental rainfall and effective rainfall, given by Banasik and Walling [3].

Table 1. The measured events in Zagożdżonka basin at Czarna and results of computation

No.	Date of occurrence	Rainfall P	Runoff H	Peak discharge Q_{max}	Lag time of runoff Lag	Lag time of sediment yield - Lag_S	Lag_S/Lag
		[mm]	[mm]	[m^3s^{-1}]	[h]	[h]	[-]
1	08.03.2000	19.2	2.39	1.52	7.27	5.97	0.82
2	28.03.2000	11.1	0.25	0.34	5.45	5.29	0.97
3	29.07.2000	48.3	1.37	0.69	4.53	3.22	0.71
4	17.09.2000	36.4	0.51	0.35	4.52	4.36	0.96
5	19.03.2001	7.90	0.32	0.24	6.72	5.34	0.79
6	24.03.2001	5.70	0.20	0.22	7.35	7.86	1.07
7	28.03.2001	3.80	0.22	0.24	8.00	8.86	1.11
8	29.03.2001	3.00	0.24	0.24	9.84	10.2	1.04
9	20.04.2001	7.80	0.48	0.25	11.5	10.2	0.89
10	22.04.2001	18.9	2.48	1.04	6.55	5.87	0.90
11	24.04.2001	25.4	5.16	2.08	6.92	5.38	0.78
12	12.02.2002	7.40	0.51	0.50	8.00	7.73	0.97
13	26.02.2002	9.10	1.11	0.80	8.41	8.17	0.97
14	27.05.2002	60.9	0.49	0.88	2.42	1.63	0.67
15	14.01.2003	14.0	2.24	1.71	10.3	8.32	0.81
16	20.03.2004	12.1	0.80	0.61	6.36	6.08	0.96
17	25.03.2004	4.60	0.58	0.38	8.99	7.59	0.84
18	07.04.2004	18.5	2.13	0.81	8.99	7.22	0.80
19	17.04.2004	12.9	0.56	0.24	9.40	8.59	0.91
Range		3.0-60.9	0.20-5.16	0.22-2.08	2.42-11.5	1.63-10.2	0.67-1.11
Average		17.2	1.16	0.69	7.45	6.73	0.89
Standard deviation		15.7	1.25	0.55	2.23	2.25	0.12

The rainfall depth P associated with the 19 events, measured at the gauging station of Czarna, varied from 3.0 mm to 60.9 mm, with the average value of 17.2 mm, and effective rainfall depth H varied from 0.20 mm to 5.16 mm, with the average value 1.16 mm. The peak discharges Q_{max} have a range from 0.22 m^3s^{-1} to 2.08 m^3s^{-1}, with the average value of 0.69 m^3s^{-1}. The lag time of runoff values varied from 2.42 h to 11.5 h, with the average value of 7.45 h, while the lag time of sediment yield varied from 1.63 h to 10.2 h, with the average value of 6.73 h. It can be observed, that the lag time of runoff has been in most of cases longer than lag time of sediment yield (for 16 out of 19 events). On the basis of estimated lag times, the ratio of Lag_S/Lag has been computed. The value of the ratio varied from 0.67 to 1.11, with the mean value of 0.89, and the standard deviation 0.12.

Table 2. The measured events in Zagożdżonka basin at Płachty and results of computation

No.	Date of occurrence	Rainfall P	Runoff H	Peak dischargeQ_{max}	Lag time of runoff Lag	Lag time of sediment yield – Lag_S	Lag_S/Lag
		[mm]	[mm]	[m^3s^{-1}]	[h]	[h]	[-]
1	01.06.1980	57.5	1.10	1.69	6.66	4.11	0.62
2	21.06.1991	19.2	0.43	0.93	7.86	3.95	0.50
3	13.06.1992	13.6	0.10	0.31	7.33	5.48	0.75
4	07.09.1992	57.7	1.02	0.62	10.5	5.29	0.51
Range		13.6-57.7	0.10-1.10	0.31-1.69	6.66-10.5	3.95-5.48	0.50-0.75
Average		37.0	0.66	0.89	8.08	4.71	0.59
Standard deviation		23.9	0.48	0.59	1.66	0.79	0.12

The four analysed events at Płachty gauging station have rainfall depth from 13.6 mm to 57.7 mm, with the average value of 37.0 mm, and effective rainfall depth from 0.10 mm to 1.10 mm, with the average value of 0.66 mm. The peak discharges have a range from 0.31 m^3s^{-1} to 1.69 m^3s^{-1}, with the average value of 0.89 m^3s^{-1}. The Lag values varied from 6.66 h to 10.5 h, with the average value of 8.08 h, while Lag_S values varied from 3.95 h to 5.48 h, with the average value of 4.71 h. The lag time of runoff has been in each cases longer than lag time of sediment yield. The value of the ratio Lag_S/Lag varied from 0.50 to 0.75, with the average value of 0.59, and the standard deviation 0.12.

Table 3. The measured events in Bauna basin at Kirchbauna and results of computation

No.	Date of occurrence	Rainfall P	Runoff H	Peak dischargeQ_{max}	Lag time of runoff Lag	Lag time of sediment yield – Lag_S	Lag_S/Lag
		[mm]	[mm]	[m^3s^{-1}]	[h]	[h]	[-]
1	16.07.2000	7.76	0.59	1.52	5.44	4.33	0.80
2	25.07.2000	8.67	0.75	1.78	3.22	1.76	0.55
3	27.07.2000	7.73	0.38	2.49	3.28	2.43	0.74
4	29.07.2000	3.30	0.22	1.38	2.33	1.37	0.59
5	02.08.2000	1.11	1.05	4.90	3.17	1.56	0.49
6	08.08.2000	3.18	0.25	0.93	4.00	2.65	0.66
7	15.08.2000	7.59	0.56	1.67	5.16	3.62	0.70
8	19.08.2000	24.8	3.68	16.6	2.48	1.57	0.63
9	21.08.2000	8.09	1.22	3.71	5.79	3.16	0.55
10	22.08.2000	5.75	0.53	1.81	4.46	4.16	0.93
Range		1.11-24.8	0.22-3.68	0.93-16.6	2.33-5.79	1.37-4.33	0.49-0.93
Average		7.80	0.92	3.67	3.93	2.66	0.66
Standard deviation		6.49	1.02	4.69	1.24	1.11	0.13

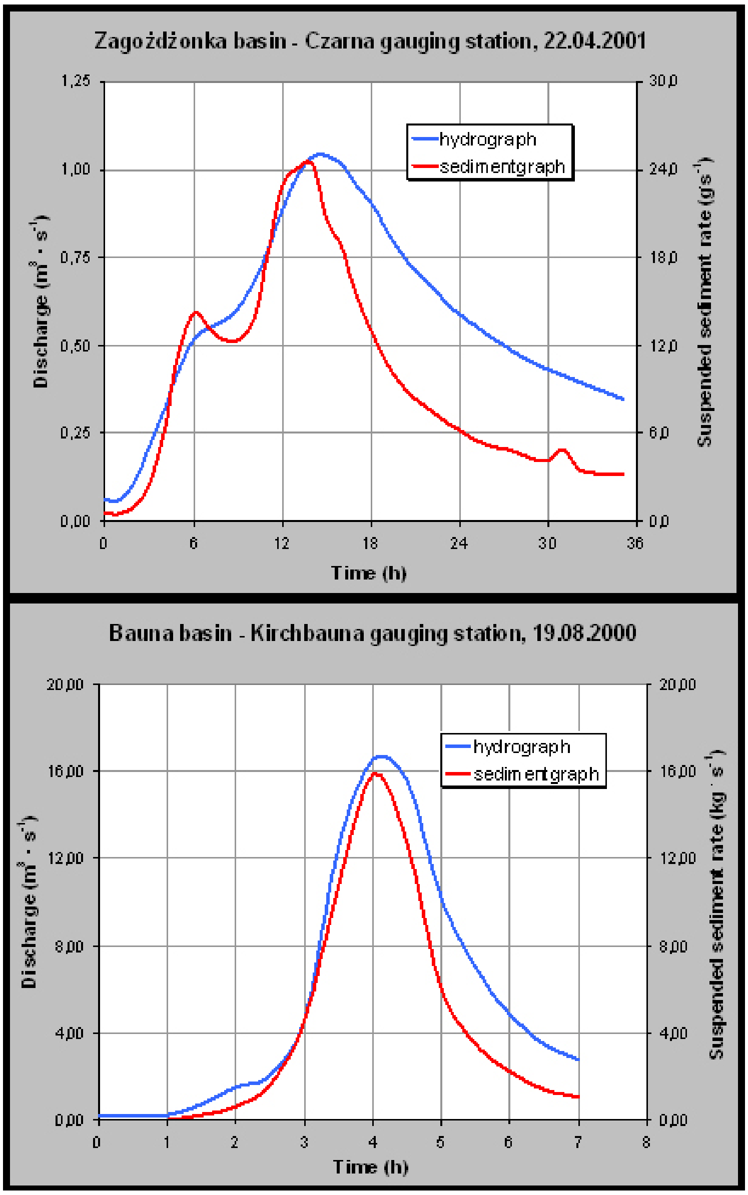
The rainfall depth associated with the 10 events, recorded in the Bauna river basin, varied from 1.11 mm to 24.8 mm, with the mean value of 7.80 mm, and effective rainfall depth varied from 0.22 mm to 3.68 mm, with the average value of 0.92 mm. The peak discharges have a range from 0.93 m^3s^{-1} to 16.6 m^3s^{-1}, with the average value of 3.67 m^3s^{-1}. The lag values varied from 2.33 h to 5.79 h, with the average value of 3.93 h, while Lag_S values varied from 1.37 h to 4.33 h, with the average value of 2.66 h. The lag time of runoff has been longer than the lag time for sedimentgraph for all of cases. The value of the ratio Lag_S/Lag varied from 0.49 to 0.93, with the average value of 0,66, and the standard deviation 0.13.

On the basis of estimated lag times of runoff (Lag) and lag times of sediment yield (Lag_S) in three investigated basins, a regression relationship on the form $Lag_S = a \cdot Lag$ was established:

- Zagożdżonka basin:
  – at Czarna gauging station: $Lag_S = 0.91$ Lag (with the correlation coeff. $R = 0.93$),
  – at Płachty gauging station: $Lag_S = 0.57$ Lag ($R = 0.60$),
- Bauna basin at Kirchbauna gauging station: $Lag_S = 0.69$ Lag ($R = 0.86$).

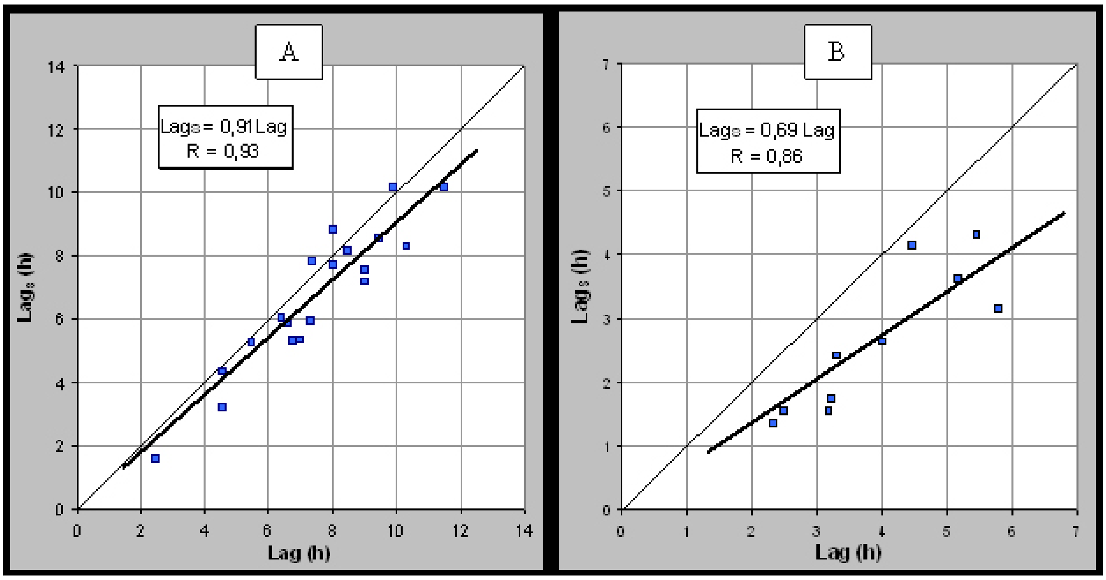
The value of the parameter "a" of the established relationships less than 1, shows that lag time of sediment is smaller than lag time of runoff. It is usually means also that peak of suspended sediment concentrations appears before peak of hydrograph. The two exemplary events, i.e. hydrographs and sedimentgraphs, registered in the Zagożdżonka basin at Czarna gauging station and in the Bauna basin, are shown in Fig. 3.

Fig. 3. The exemplary events recorded in the Zagożdżonka basin and in the Bauna basin



The examined relationships for the Zagożdżonka basin at Czarna gauging station and for the Bauna basin are very strong and strong, respectively (Fig. 4), i.e. the correlation coefficient is longer then 0.9 and 0.7, respectively.

Fig. 4. The relationship between Lag_S and Lag in Zagożdżonka basin at Czarna gauging station (A) and in Bauna basin (B)



The relationship for the Zagożdżonka basin at Płachty gauging station associated with the 4 events is statistical insignificant.

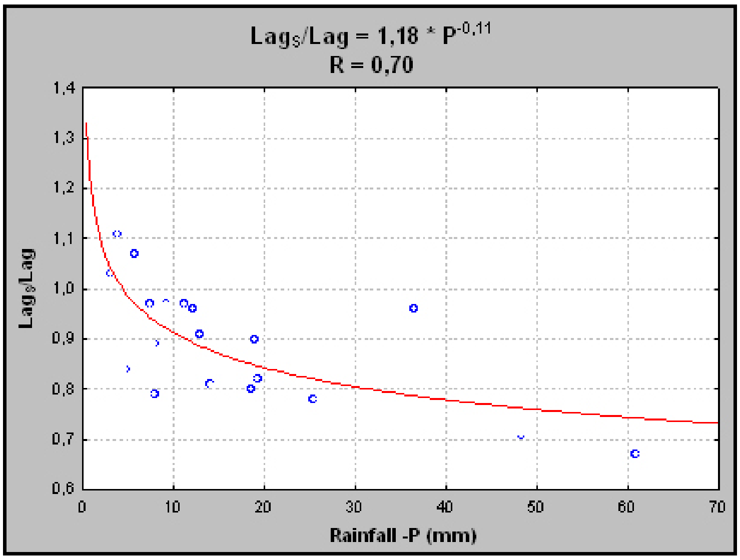
Relationship of Lag_S/Lag vs. parameters of events

The data from the Zagożdżonka basin at Czarna gauging station (where the largest number of events were recorded, i.e. 19 events), have been used to find a relationship between values of the ratio Lag_S/Lag and selected parameters of the events. The following parameters have been considered: total and effective rainfall depth (mm), intensity of total and effective rainfall depth (mm/h), peak discharge (m^3s^{-1}). The Analysis was carried out using of software of "Statistica". The highest correlation has been found between Lag_S/Lag and rainfall depth – P (Fig. 5) on the form:

$$Lag_S/Lag = 1.18\ P^{-0.11} \tag{6}$$

with correlation coefficient R = 0.70.

Fig. 5. The relationship between Lag_S/Lag and rainfall depth – P in Zagożdżonka basin to Czarna gauging station



It can be seen from Fig. 5, that the values Lag_S/Lag are decreasing when the total rainfall depth P for the events are increasing. The Analyse of the remaining factors indicate for lower correlation, i.e. with effective rainfall depth – R = 0.57, with peak discharge – R = 0.57, with intensity of effective rainfall depth – R = 0.53 and with intensity of total rainfall – R = 0.47.

CONCLUSIONS

The lag time of runoff – Lag, the lag time of sediment yield – Lag_S, and their relationship for a three small basins has been investigated. The two of the basins, i.e. Zagożdżonka basin at Czarna and Płachty gauging station located in central Poland, are a lowland agricultured type. The third one, i.e. Bauna basin located in Germany, is a submontain and relatively high urbanized basin. The analysis shows that:

1. Lag time of runoff – Lag is in most of the cases longer than lag time of sediment yield – Lag_S (for 30 of 33 analysed events in three basins).
2. A significant linear relationship exists between Lag_S and Lag.
3. The average values of the ratio of Lag_S/Lag in investigated basins, are as follow:

- Zagożdżonka basin at Czarna – 0.89 (with the range from 0.67 to 1.11),
- Zagożdżonka basin at Płachty – 0.59 (0.50-0.75),
- Bauna basin at Kirchbauna – 0.66 (0.49-0.93).

4. In the Zagożdżonka basin at Czarna gauge station the relationship between Lag_S/Lag and rainfall depth – P has been found on the form: $Lag_S/Lag = 1.18\ P^{-0.11}$.

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Mariusz Barszcz
Department of Water Engineering and Environmental Recultivation,
Warsaw Agricultural University, Poland
Nowoursynowska 159, 02-776 Warsaw, Poland
phone: +22 5935284, +22 5935280
email: barszcz@alpha.sggw.waw.pl

Kazimierz Banasik
Department of Water Engineering and Environmental Recultivation,
Warsaw Agricultural University, Poland
Nowoursynowska 159, 02-776 Warsaw, Poland
phone: +22 5935284, +22 5935280
email: banasik@alpha.sggw.waw.pl

Frank Tönsmann
Department of Hydraulic and Water-Resources Engineering,
University of Kassel, Germany
Kurt Wolters-Strasse 3, 34-109 Kassel, Germany
email: ftoensm@gmx.net
