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Variability in runoff from a small agricultural catchment – based on long term monitoring data

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Introduction

Accelerated changes of land use, population and climate are causing spatial and temporal changes in renewable water resources. For better understanding of the changes and for effective managing of the water resources, hydrological investigation in river catchments are carried out around the world. A special case of the investigation is formed by study on the hydrological processes in site-specific, small catchments (Fernandez and Garbrecht 1994; Kostadinov and Mitrovic 1994; Walker et al. 2000; Mitchell at al. 2001 & 2002; Endale et al. 2006; Garbrecht 2008; Amatya and Trettin 2011; Deelstra et al. 2011).

In this chapter results of long term investigation in a small agricultural, lowland catchment of the Zagożdżonka River, located in the center of Poland is presented. Also hydrological characteristics of a neighboring, shortly monitored catchment of the Zwoleńka River, with very valuable ecological sites, have been demonstrated.

Hydrological investigation in the catchment of Zagożdżonka

Location and characteristics of the investigated area

The Zagożdżonka catchment (Figure 1.1) is a small agricultural, lowland catchment, located in central Poland, about 100 km south of Warsaw. The Zagożdżonka River is left tributary of the Vistula River with its outlet (N:51°39’28”; E:21°29’13”) near Kozienice town. Hydrological field investigations of the Zagożdżonka River, at Płachty (N:51°26’43.8”; E:21°27’35.6”), have been carried out by the Department of Water Engineering and Environmental Restoration of Warsaw University of Life Sciences since 1962. In the first period, the river water stages have been recorded by an observer,

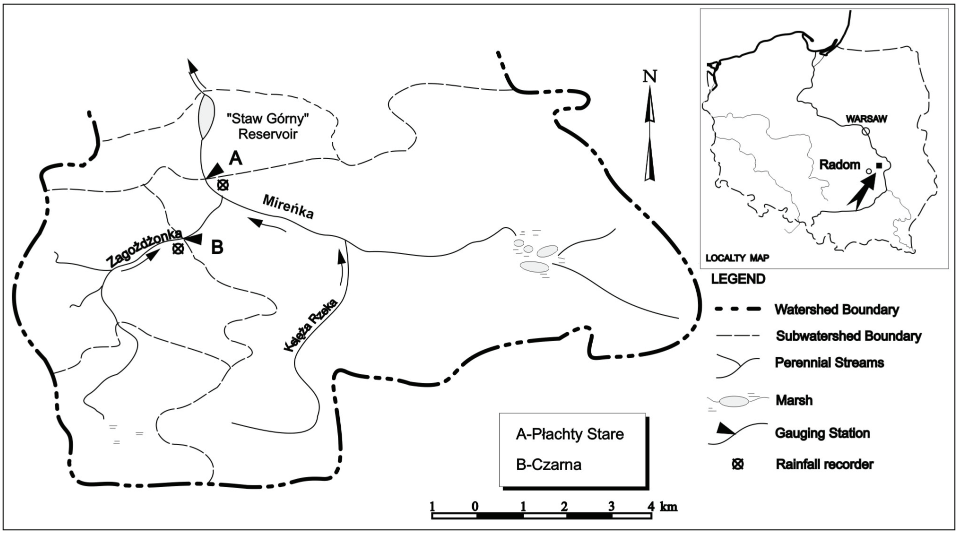

FIGURE 1.1. Locality map of the Zagożdżonka catchment and gauging stations

who was reading staff gauge three times a day, except flood periods when reading was usually carried out each hour. Since 1980 monitoring of the river stages has been carried out with the use of mechanical water stage recorder, and since middle of the last decade of the previous century with the use of electronic system for recording, logging and transmitting the data. In the recent periods, the traditional reading of staff gauge has been continued for correcting the records once a day. For precise estimation of river flow a rating curve has been established and verified at least once a year based on hydrometric measurements. View of this natural channel gauging station at Płachty is shown on Figure 1.2 and view of the meteorological site at Czarna on Figure 1.3.

Monitoring of river flow at the Czarna measuring weir gauging station, located upstream of Płachty, 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 Płachty gauging station, whereas the subcatchment area at Czarna is 23.4 km^2. Selected results of filed investigation carried out at Czarna river gauge are demonstrated in other chapter.

The lowland catchment of the Zagożdżonka River, has a typical topography for this part of Poland. The mean elevation of the catchment is about 163 m above sea level, and absolute relief is 37.0 m i.e. from 147.5 to 184.5 m asl (upstream of A, Figure 1.1). 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

FIGURE 1.2. View of the stream gauge station at Płachty (photo is looking downstream)

FIGURE 1.3. Meteorological gauging station at Czarna in the Zagożdżonka catchment

catchment, constitute a significant part of the area (i.e. 3.8 km^2 and 19.8 km^2 upstream of the Czarna and Płachty gauging stations, respectively).

Land use is dominated by arable land (small grain and potatoes), which occupies about 48% of the catchment, and about 41% is covered by forest and 11% is pasture (Banasik 1994). Sandy soils are dominant in the watershed area (loamy sand, 27.2%; light loamy sand, 60.6%; and organic soils, 12.1%).

Precipitation and runoff – source of data

The mean annual precipitation and runoff for the hydrological years 1963–2010 are estimated at 611 mm and 106 mm, respectively, based on data collected by the Department of Water Engineering of Warsaw University of Life Sciences – SGGW at Płachty, except precipitation data for the period 1963–1982, which were taken from available publications of the Polish hydro-meteorological service (IMGW) for the nearest rain gauge, Zwoleń (located about 11.7 km south-east 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

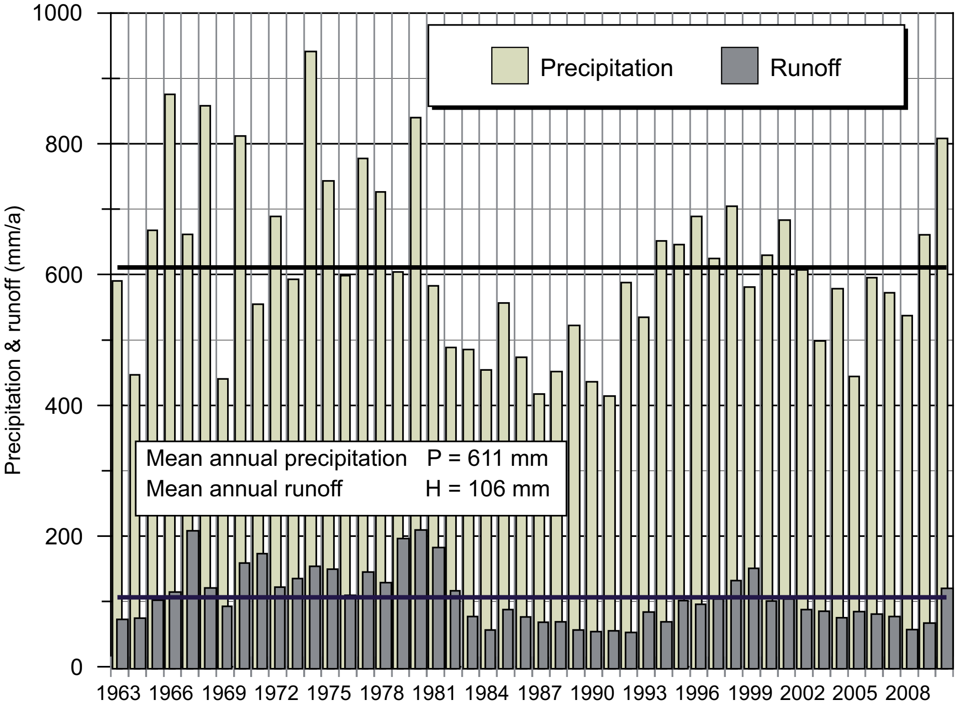

FIGURE 1.4. Annual precipitation and runoff depths for the Zagożdżonka catchment upstream of Płachty gauge for the hydrological years of 1963–2010

runoff to precipitation) for the area to the Płachty gauging station range from 0.088 (1992) to 0.320 (1979), with a mean value of 0.173. Annual values of precipitation and runoff are shown in Figure 1.4. Statistical characteristics of the analysed series are presented in Table 1.1.

TABLE 1.1. Main parameters of statistical series of precipitation, runoff and runoff coefficient for Zagożdżonka catchment at Płachty gauge for the period of 48 years (1963–2010)

Characteristics	Mean value	Standard deviation	Relative standard deviation	Skewness
1	2	3	4	5
Precipitation *P* (mm)	611.2	129.4	0.212	0.558
Runoff *H* (mm)	105.9	41.9	0.392	0.881
Runoff coefficient *c* (–)	0.173	0.057	0.327	1.276

Precipitation and runoff in the period of project investigation on the background of long term data

The main monitored parameters in the Zagożdżonka catchment at Płachty gauge in the period of investigation i.e. in the three hydrological years 2008–2010 (from Nov. 1, 2007 until Oct. 31, 2010) are presented in Table 1.2 and Figure 1.5. Mean annual values of precipitation and runoff in the period 2008–2010 have been 668.7 mm and 80.6 mm respectively. In respect of precipitation the period 2008–2010 has been wetter than average year (611.2 mm) and in respect of runoff; the period 2008–2010 was dryer than average year (105.9 mm). Taking into account individual annual values of the investigated parameters one can notice that in respect of precipitation two years (2009 and 2010) were wetter than average year, and in respect of runoff only one year (2010) was wetter than average year. Both, annual precipitation and runoff depths increased each year from 2008 to 2010.

Monthly distributions of precipitation, runoff and discharge for the period of 2008–2010 are presented in Table 1.2, and mean values of the characteristics for the period of 48 years also in Figure 1.6. One can notice from data presented in Table 1.2 and Figure 1.6, that in respect of mean long term precipitation, the wettest month is July, with rainfall depth 78.7 mm, i.e. 12.9% of annual value, and the driest one is January with the equivalent of rainfall and snowfall depth of 31.6 mm i.e. 5.2% of annual value. In respect of mean long term runoff the wetter month is March, with runoff depth 15.5 mm, i.e. 14.7% of annual values and the dryer on is July with runoff depth 5.4 mm i.e. 5.1% of mean annual runoff. In the period of investigation (2008–2010) March and July were on average also the most extreme months, i.e. the wettest and the driest, in term runoff as in the period 1963–2010. It has not been the case in respect of precipitation, as the wettest and driest months were September and April, respectively.

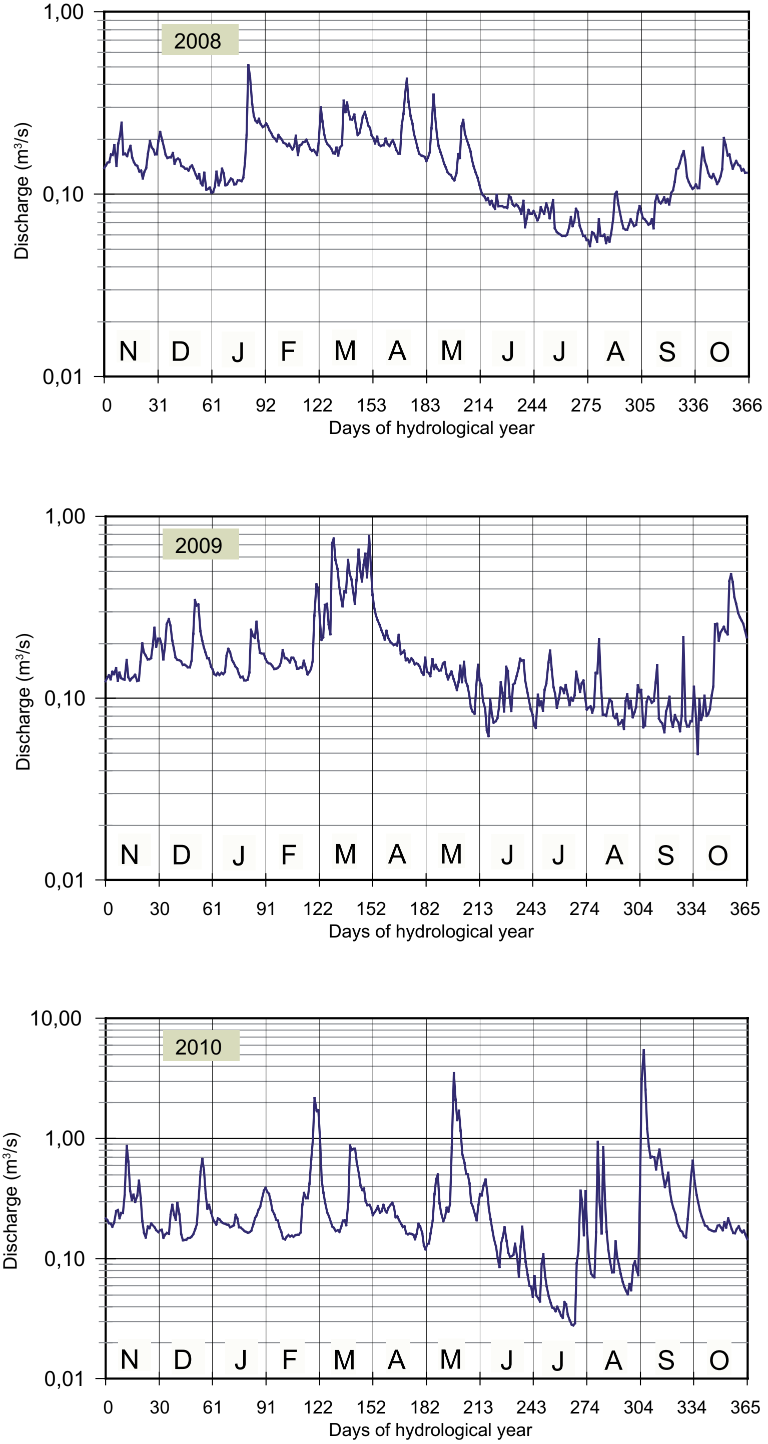

FIGURE 1.5. Annual discharge hydrographs of the Zagożdżonka River at Płachty gauge for hydrological years of 2008, 2009 and 2010

TABLE 1.2. Monthly and annual values of precipitation and discharge in the Zagożdżonka river at Płachty gauge in the period of 2008–2010, with mean values for the period of project investigation and long term data (1963–2010)

Precipitation (mm)													
Period	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX	X	annual
2008	43.0	11.5	50.4	13.2	60.3	38.6	62.7	26.2	53.0	74.3	59.9	44.2	537.3
2009	29.0	38.5	22.8	54.4	82.3	0.3	68.0	101.8	84.7	59.7	36.0	83.4	660.9
2010	47.2	56.7	31.1	36.4	22.3	19.4	136.9	74.8	96.3	106.6	159.4	20.9	808.0
P(08-10)	**39.7**	**35.6**	**34.8**	**34.7**	**55.0**	**19.4**	**89.2**	**67.6**	**78.0**	**80.2**	**85.1**	**49.5**	**668.7**
P(63-10)	**43.5**	**38.9**	**31.6**	**31.9**	**33.1**	**43.9**	**62.6**	**75.2**	**78.7**	**72.5**	**57.1**	**42.3**	**611.2**
Relative P(%)	7.1	6.4	5.2	5.2	5.4	7.2	10.2	12.3	12.9	11.9	9.3	6.9	100.0
Discharge (m³/s)													
Period	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX	X	annual
2008	0.164	0.145	0.185	0.192	0.230	0.213	0.172	0.087	0.071	0.068	0.104	0.139	0.147
2009	0.152	0.199	0.162	0.168	0.448	0.202	0.133	0.109	0.110	0.095	0.089	0.212	0.174
2010	0.274	0.240	0.218	0.385	0.424	0.212	0.601	0.169	0.083	0.168	0.789	0.200	0.313
SQ(08-10)	**0.197**	**0.195**	**0.188**	**0.249**	**0.367**	**0.209**	**0.302**	**0.122**	**0.088**	**0.110**	**0.328**	**0.184**	**0.211**
SQ(63-08)	**0.255**	**0.303**	**0.319**	**0.366**	**0.477**	**0.389**	**0.232**	**0.192**	**0.166**	**0.183**	**0.187**	**0.254**	**0.277**
Relative SQ(%)	92.9	109.5	115.2	132.3	172.6	140.8	83.8	69.3	59.9	66.3	67.7	92.0	**100.0**
Runoff (mm)													
Period	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX	X	annual
2008	5.2	4.6	5.8	6.0	7.2	6.7	5.4	2.7	2.2	2.1	3.3	4.4	55.7
2009	4.8	6.5	5.3	4.9	14.6	6.4	4.3	3.4	3.6	3.1	2.8	6.9	66.5
2010	8.6	7.8	7.1	11.3	13.8	6.7	19.5	5.3	2.7	5.5	24.8	6.5	119.6
H(08-10)	**6.2**	**6.3**	**6.1**	**7.4**	**11.9**	**6.6**	**9.8**	**3.8**	**2.8**	**3.6**	**10.3**	**5.9**	**80.6**
H(63-10)	**8.0**	**9.8**	**10.4**	**10.7**	**15.5**	**12.2**	**7.5**	**6.0**	**5.4**	**6.0**	**5.9**	**8.3**	**105.9**
Relative H(%)	7.6	9.3	9.8	10.2	14.7	11.6	7.1	5.7	5.1	5.6	5.6	7.8	100.0

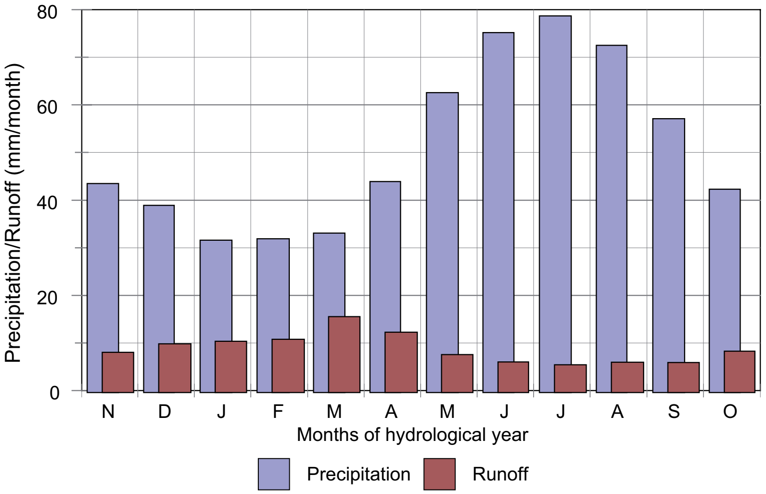

FIGURE 1.6. Mean annual distribution of precipitation and runoff in Zagożdżonka catchment at Płachty gauge for the period 1963–2010

Trend analysis of the annul precipitation, runoff and runoff coefficient

To evaluate the trend of the three parameters, the Mann-Kendall test was selected as it is simple in use and it is often applied for climatological and hydrological trend analysis (Khambhammettu 2005; Kundzewicz et al. 2005; Hamed 2008; Sahooa and Smith 2009; Węglarczyk 2010). The analysis procedure is presented with the use of annual values of precipitation, runoff and runoff coefficient, as described earlier. The Mann-Kendall test is a non-parametric test for identifying trends in time series data. The test compares the relative magnitudes of particular data rather than the data values themselves. One benefit of this test is that the data does not need to conform to any particular distribution. The data values are evaluated as an ordered time series. Each data value is compared to all subsequent data values. The initial value of the Mann-Kendall statistic, S, is assumed to be 0 (*e.g.*, no trend). If a data value from a later time period is higher than a data value from an earlier time period, S is incremented by 1. On the other hand, if the data value from a later time period is lower than a data value estimated earlier, S is decremented by 1. The net result of all such increments and decrements yields the final value of S. Let $x_1, x_2, \ldots x_n$ represent n data points where x_j represents the data point at time j. Then the Mann-Kendall statistic (S) is given by:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sign(x_j - x_k) \qquad (1)$$

where:

$$sign(x_j - x_k) = \begin{cases} 1 & if \quad x_j - x_k > 0 \\ 0 & if \quad x_j - x_k = 0 \\ -1 & if \quad x_j - x_k < 0 \end{cases} \qquad (2)$$

A very high positive value of S is an indicator of an increasing trend, and a very low negative value indicates a decreasing trend. However, it is necessary to compute the probability associated with S and the sample size, n, to statistically quantify the significance of the trend (Khambhammettu 2005). The Mann-Kendall statistic S for analysed parameters, computed according to formulae 1 and 2, are given in Table 1.3.

Based on normalised test statistic Z, computed from formula:

$$Z = \frac{S - sign(S)}{VAR(S)^{1/2}} \qquad (3)$$

where $VAR(S)$ is variance of S estimated, as the sample size is large i.e. $n > 30$, by the equation:

$$VAR(S) = \frac{1}{18}\left[n \cdot (n-1) \cdot (2n+5)\right] \tag{4}$$

the probability, associated with the normalised test statistic Z, has been computed using Microsoft Excel function, ***NORMSDIST()***. The computed values of normalised test statistic Z and probability are given in Table 1.3. The trend is said to be decreasing if Z is negative and computed probability is greater than the level of significance (95% typically). So, in the case of 48 years of annual precipitation values no trend has been deducted. For both of the series of annual runoff depths and annual runoff coefficients decreased trends at the probability level of 95% have been deducted (Table 1.3). The variation of annual runoff with time is discussed in the next subchapter.

TABLE 1.3. Mann-Kendall trend results

Characteristics	Number of data	Range of the values	Mann--Kendall statistics S	Normalized test statistics Z	Probability	Trend (at 95% level of significance)
1	2	3	4	5	6	7
Precipitation P (mm)	48	414.3–941.4	–137	–1.209	0.8866	no trend
Runoff H (mm)	48	52.2–209.2	–288	–2.551	0.9946	decreasing
Runoff coefficient c (–)	48	0.088–0.320	–311	–2.755	0.9971	decreasing

Temporal variations of annual values of runoff in the period of 1963–2010

To analyze the variation of annual values of runoff from Zagożdżonka catchment at Płachty gauge with time, the relations of two types have been selected. The first one has been formed by three commonly used relationships, i.e.:

- linear trend:

$$y = a + bx \tag{5}$$

- periodic cycle

$$y = a + b\cos\left(2\pi\frac{x-c}{d}\right) \tag{6}$$

and

- linear trend with periodic cycle

$$y = a + b_1(x-c) + b_2\cos\left(2\pi\frac{x-c}{d}\right) \tag{7}$$

where:
y – dependent value (annual runoff in mm),
x – independent value (hydrological year, i.e. 1963, 1964, ... 2010),
a, b, c and d – estimated parameters.

As annual values of runoff from 1963–2010 are higher in the first part of the period with a drop at the beginning of 1980s (Figure 1.4), also two other relationships of runoff versus time are presented, one from a group of transition functions and the other one from a group of peak functions. For estimation of the parameters of the earlier and the later functions a software TableCurve 2D (Systat Software Inc. 2002) has been used. In case of the later functions the best fit functions from the both groups were selected. There has been selected the following once:

- from the set of transition functions, the Log Normal Cumulative function:

$$y = a + \frac{b}{2} erfc\left(\frac{-\ln\left(\frac{x}{c}\right)}{\sqrt{2}d} \right) \tag{8}$$

and

- from the set of peak functions, the Symmetric Double Gaussian Cumulative (SDC) function:

$$y = a + \frac{b\left[1 + erf\left(\frac{x - c + \frac{d}{2}}{\sqrt{2}e}\right)\right]\left[1 - erf\left(\frac{x - c - \frac{d}{2}}{\sqrt{2}e}\right)\right]}{\left[1 + erf\left(\frac{d}{2\sqrt{2}e}\right)\right]^2} \tag{9}$$

where:
$erf(.)$ – error function,
$erfc(.)$ – complementary error function,
a, b, c, d, and e – estimated parameters, with the TableCurve 2D software (Systat Software Inc. 2002), of the functions 8 and 9 [(a – intercept in mm; b – transition height in equation 8 and amplitude in equation 9, both in mm; c – transition center in eq. 8 and center in eq. 9, both as year; d – shape parameter in eq. 8 (–), and width in eq. 9 (year); e – shape parameter (year)].

Parameters of the relationships 5–9 as well as measure of approximation functions with the recorded annual values i.e. determination coefficients and standard errors of estimation are presented in Table 1.4. The functions are also shown in the Figures 1.7 and 1.8.

TABLE 1.4. Results of analysis of temporal variation of runoff with various statistical relationships

Temporal variation	Equation number	Values of parameters	Determination coefficient – r^2	Standard error of estimation
1	2	3	4	5
Linear trend	5	a = 2 561 b = –1.236	0.167	38.7
Periodic cycle	6	a = 105.7 b = 32.7 c = 1973.6 d = 46.0	0.298	36.3
Linear trend and periodic cycle	7	a = 120.9 b_1 = –1.64 b_2 = 34.6 c = 1975.9 d = 26.1	0.486	31.5
Log Normal Cumulative function as the best fit from transition functions	8	a = 83.0 b = 56.3 c = 1982.0 d = –5.88E-05	0.434	32.6
SDC function as the best fit form peak functions	9	a = 76.9 b = 76.3 c = 1973.6 d = 16.8 e = 0.533	0.565	29.0

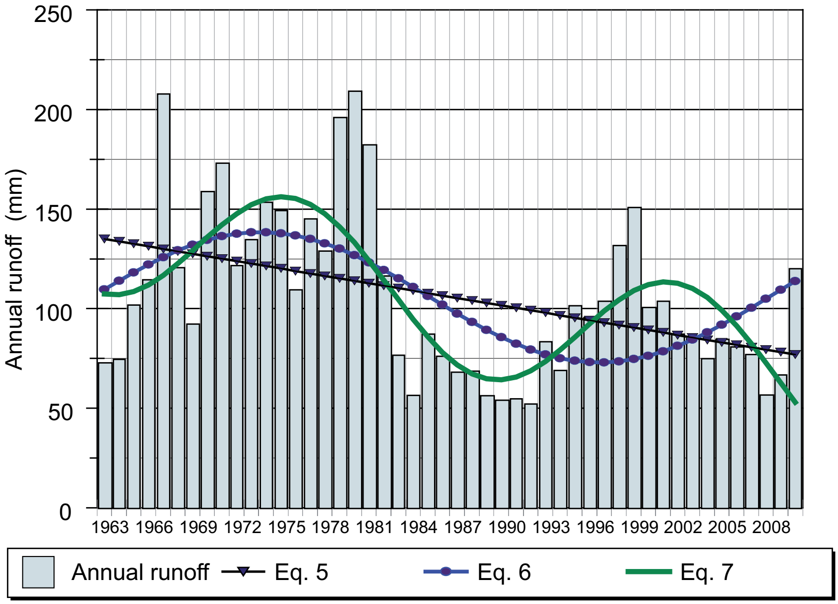

FIGURE 1.7. Approximation equations 5–7 for the annual runoff of Zagożdżonka catchment at Płachty gauge for the period 1963–2010

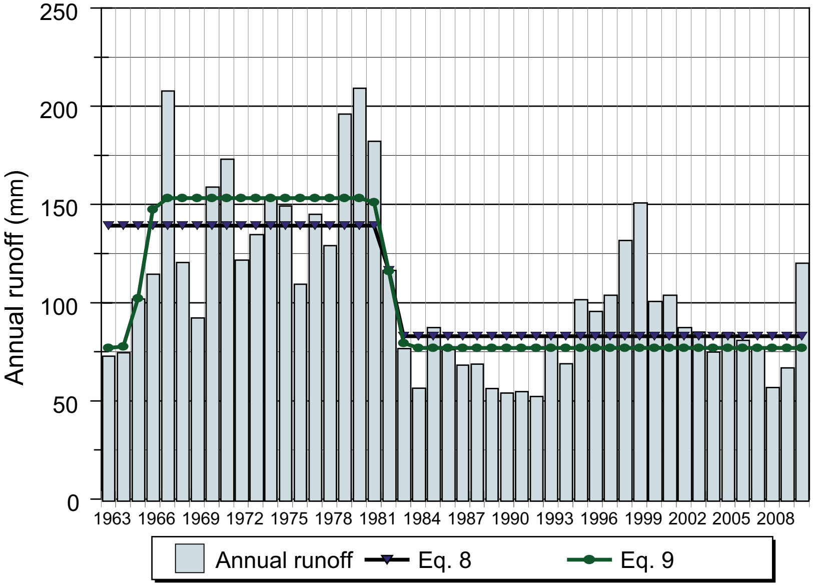

FIGURE 1.8. Approximation equations 8 and 9 for the annual runoff of Zagożdżonka catchment at Płachty gauge for the period 1963–2010

Correlation coefficient of the linear relationship (equation 5) compared with critical one confirms the significance (at the level of 95%) of the decreasing trend of annual runoff, what has been earlier ascertained by Mann-Kendall test. Correlation between the annual runoff with time (expressed as hydrological years of the period 1963–2010), measured by determination coefficient (Table 1.4, column 4), is becoming stronger for the periodic cycle (equation 6 – no trend included) and then for linear trend with periodic cycle (equation 7). Parameters of the both equations containing the trend element (i.e. eq. 5 and eq. 7) indicate mean annual decrease in runoff of 1.24 mm and 1.64 mm for the equations 5 and 7, respectively. It is worth to indicate that an early analyze of the runoff of the period of 37 years, i.e. from 1963 to 1999 (Byczkowski et al. 2001) indicated also significant decreased trend of annual runoff with the decrease of 1.36 mm per year.

The relative high values of determination coefficients of the two last relationships (equations 8 and 9), i.e. the Log Normal Cumulative function and the Symmetric Double Gaussian Cumulative (SDC) function, containing a sudden drop of runoff at the beginning of 1980s (see parameter c in eq. 8 and $c + d/2$ in eq. 9) may also indicate an existence of other reasons influencing on the annual runoff than climate change. This however would require deeper analysis of potential causes as meteorological parameters, land use changes and stream engineering works in the catchment, and increase of the analyzed sample i.e. to extend the period of observation and/or including earlier period into the analyze by identifying earlier annual runoff values.

Flow duration curve for the Zagożdżonka River and the Zwoleńka River

The Flow Duration Curve (FDC) is used here to express the mean variation in river flow over the year for both the Zagożdżonka River at Płachty gauge and the Zwoleńka River at Siekierka gauge. The first one, as described earlier, has long term (48 year) discharge record, whereas the other one has been monitored only during the period of project investigation (July 2008 – October 2010).

The FDC shows how flow is distributed over a year. The vertical axis gives the flow and the horizontal one gives the percentage of the year that the flow exceeds the value given on the y-axis. Hence, for example, the FDC can immediately indicate the level of flow which will be available for at least 50% of the year (known as Q_{50}). The flow exceeding the given value for 95% of the year (Q_{95}) is often taken as the characteristic value for minimum river flow.

FDCs are often very similar for a region, but can be affected by soil conditions, vegetation cover, and to a lesser extent by catchment shape. They are also modified by man-made reservoirs, abstractions and discharges. A flatter FDC, characterizing more uniform river flow, means that the total annual flow will be spread more evenly over the year, giving useful flow for a longer period, and less severe floods.

The FDCs for the Zagożdżonka River at Płachty gauge for the two periods 2008–2010 and 1963–2010 in log-normal scale are shown on Figure 1.9. Flows exceeded the given value for: 0.5%, 1%, 5%, 10%, 20%, 50%, 80%, 90%, 95%, 99% and 99.5% of the year for both FDCs, which is also presented in Table 1.5. The FDC for the period 2008–2010, being other representation of the three annual hydrographs presented on Figure 1.5, confirms the data presented in Table 1.2 that the three years of project realisation were, on average, drier than average year of the period 1963–2010. The relative flow in the period of 2008–2010 vs. flow of 1963–2010 changes with the time the flow is exceeded (see Table 1.5, column 4). The lowest ratio is to be found for exceedance probability of 10% (0.690) and of 1% (0.692) and the higher ratio is to be found for exceedance probability of 99% (0.944) and 99.5% (0.937). One can find from the data of Table 1.2 that the ratio of mean annual discharge from the period of project conducted (2008–2010) versus long term (1963–2010) average discharge (0.211 m^3/s vs 0.277 m^3/s) is 0.762.

The above data have confirmed that the three year period of investigation, as significantly drier than average year, cannot deliver sufficient information for hydrological characteristics of a catchment, which has not been gauged before, as it was with the Zwoleńka River.

The Zwoleńka River, bordered to the Zagożdżonka River and, like the latter one, is a left tributary of the Vistula River, with outlet at her middle reach (N:51°16’16.6”;

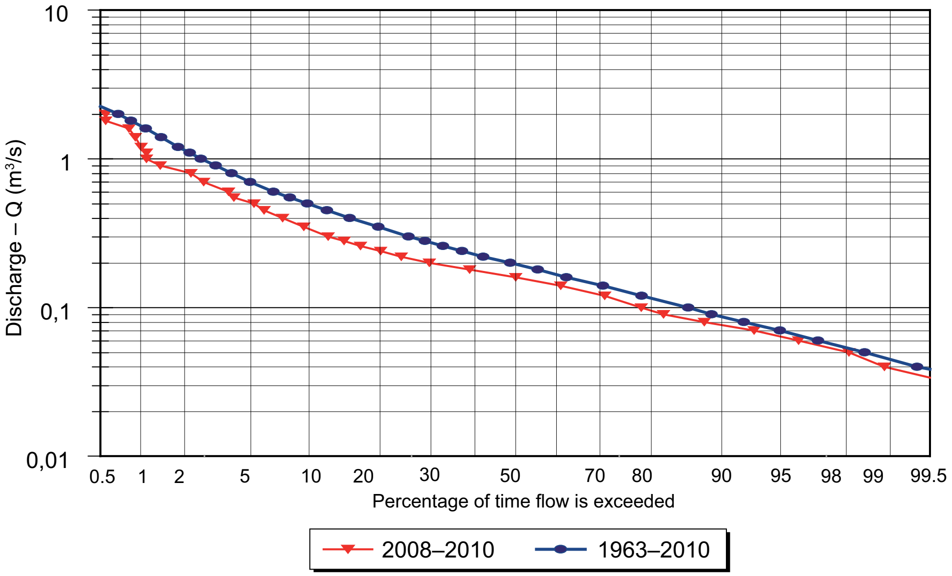

FIGURE 1.9. Flow duration curves of daily discharges for Zagożdżonka catchment at Płachty gauge for the period 2008–2010 and 1963–2010

TABLE 1.5. Selected ordinates of FDCs shown in Figure 1.8

Percentage of time the flow is exceeded	Daily flow (m³/s) in the period		Ratio of flow in the period of 2008–2010 vs 1963–2010
	2008–2010	1963–2010	
1	2	3	4
0,5	1,923	2,221	0,866
1	1,161	1,678	0,692
5	0,503	0,696	0,723
10	0,339	0,492	0,690
20	0,241	0,346	0,697
50	0,160	0,196	0,817
80	0,096	0,116	0,828
90	0,075	0,086	0,872
95	0,064	0,069	0,925
99	0,040	0,042	0,944
99,5	0,034	0,036	0,937

E:21°49’24.2”). Zwoleńka catchment with its area of 230.2 km^2 is located south-east of the Zagożdżonka catchment. The Zwoleńka valley belongs to the most valuable natural treasures of Mazowsze region. There are number of habitats protected by “Natura 2000” program within the site and numerous rare plant and animal species. The symbol of the area is European pond turtle appearing in the Borowiec Nature Reserve, i.e. in the valley of lower course of the Zwoleńka River (Mitrus and Zemanek 2004, Mitrus

2005). This has been the main reason to undertake the investigation of hydrological characteristics the catchment, which had not been monitored earlier. The river gauging station of Siekierka (N:51°17'25.0"; E:21°41'42.2") is located within the "Natura 2000" area, ca 7.0 km upstream of the Borowiec Nature Reserve (measured along a straight line), and is closing catchment area of 186.8 km^2 (Figure 1.10).

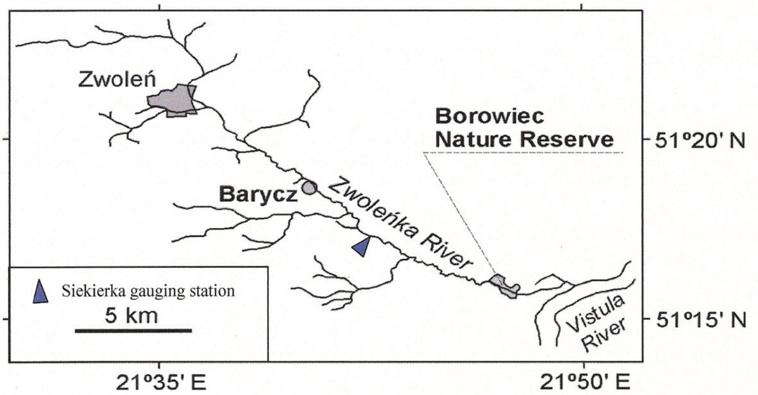

FIGURE 1.10. Locality map of the Zwoleńka River with the Siekierka gauging station

Apart from the difference in catchment area, the two river catchments have various ratio of afforestation (i.e. 0.41 and 0.24 in Zagożdżonka and Zwoleńka, respectively), various shape factor defined as the drainage area divided by the square of the main channel length (0.60 and 0.29), different mean slope of the river channel (0.0024 and 0.0016) as well as shape and soils of their valleys, which in case of the Zwoleńka River is significantly wider (up to 500 m) and is characterized by mainly organic soils (Popek 2011).

The flow duration curve (FDC) for the Zwoleńka River at Siekierka gauge has been constructed by finding relationship between river discharges of Zwoleńka vs discharge of Zagożdżonka in the gauging stations, which in turn has been used for reproducing daily discharges for Zwoleńka, based on long term data of the Zagożdżonka River at gauge Płachty. For constructing the relationship of discharges in the two rivers, 40 corresponding values of instantaneous river flows have been used, from which 26 were semi-simultaneous current meter measurements and 14 were peak flow hydrograph values, estimated on electronic water level records and rating curves. The regression relationship between discharges in the two rivers, shown in Figure 1.11, was established as:

$$Q_{\mathrm{Zwol}} = 1.883 \cdot Q_{\mathrm{Zag}}^{\;0.788} \tag{10}$$

where:

Q_{Zwol} – discharge of the Zwoleńka River at the Siekierka gauge (m^3/s),

Q_{Zag} – discharge of the Zagożdżonka River at the Płachty gauge (m^3/s).

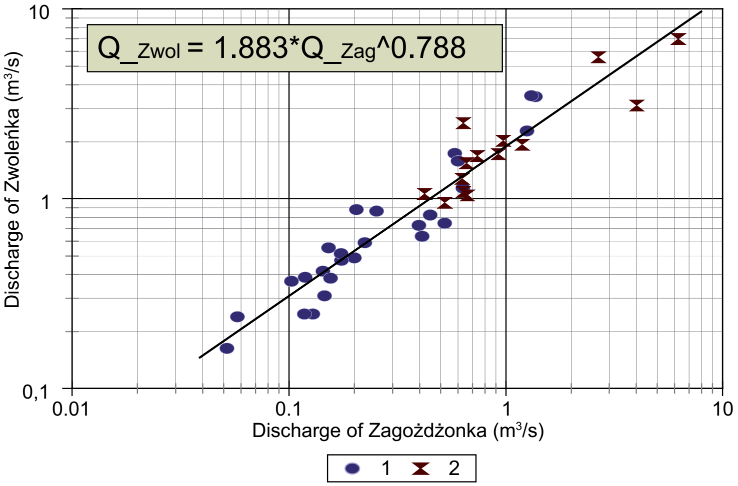

FIGURE 1.11. Corresponding discharges of the Zagożdżonka River at Płachty gauge and the Zwoleńka River at Siekierka gauge estimated on the base of semi-simultaneous flow meter measurements (1) and peak hydrograph records (2)

The determination coefficient, for logarithmic values of discharges, of the relationship 10 is 0.909 (i.e. correlation coefficient $r = 0.95$ with $r_{critical} = 0.31$ at 95% level of significance).

Mean annual FDC for the Zwoleńka River at Siekierka gauge, established on the base of long term daily discharges of Zagożdżonka at Płachty and the relationship 10, is shown in Figure 1.12 together with FDC of Zagożdżonka. Selected ordinates of FDCs shown in Figure 1.12 are also presented in Table 1.6, with the computed specific discharges for both rivers.

Analyzing the specific discharges shown in Table 1.6, one can find out that there is an important difference in characteristic of the two rivers, i.e. higher values in the Zwoleńka of low flow: Q_{90}, Q_{95}, Q_{99} and $Q_{99,5}$ i.e. higher in the range of 40–68% than in Zagożdżonka, and lower values for discharges with short time of exceedance i.e Q_{10}, Q_{5}, Q_{1} and $Q_{0,5}$.

Mean annual specific discharge is, for both rivers; very close i.e. 3.36 and 3.44 dm³/s/km² for Zagożdżonka and Zwoleńka, respectively.

Higher retention i.e. higher low specific discharge and lower flood once, is typical for larger catchments. In this case however, there might have been also other more influential reasons of the difference in the shape of FDCs as:

- large forest areas in the Zagożdżonka catchment (41%), consuming water for evapotranspiration, are decreasing the dry period discharge,
- meandering channel in a wide valley of organic soils, lower river channel slope and elongated shape (lower shape factor) of the Zwoleńka catchment are the factors, which reduce the high flow discharges.

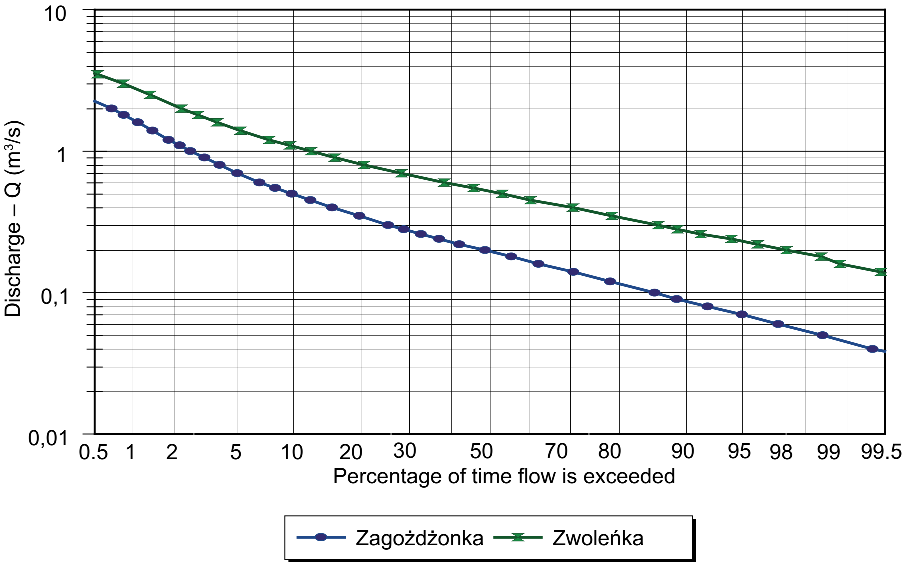

FIGURE 1.12. Flow duration curves of daily discharges for Zagożdżonka catchment at Płachty gauge and for Zwoleńka catchment at Siekierka gauge for the period of 1963–2010

TABLE 1.6. Selected ordinates of FDCs of the Zagożdżonka River and the Zwoleńka River for the period 1963–2010

Percentage of time the flow is exceeded	Daily flow from the catchment (m^3/s)		Specific discharge (dm^3/s/km^2)		Ratio of specific discharges of Zwoleńka vs Zagożdżonka
	Zagożdżonka	Zwoleńka	Zagożdżonka	Zwoleńka	
1	2	3	4	5	6
0,5	2,221	3,529	27,0	18,9	0,70
1	1,678	2,830	20,4	15,1	0,74
5	0,696	1,415	8,45	7,57	0,90
10	0,492	1,076	5,97	5,76	0,96
20	0,346	0,815	4,20	4,37	1,04
50	0,196	0,520	2,38	2,79	1,17
80	0,116	0,345	1,41	1,85	1,31
90	0,086	0,272	1,04	1,46	1,40
95	0,069	0,229	0,84	1,23	1,46
99	0,042	0,155	0,51	0,83	1,63
99,5	0,036	0,137	0,44	0,73	1,68
Mean value	**0,277**	**0,643**	**3,36**	**3,44**	**1,03**

Conclusions

Results of long term hydrological investigation have delivered very valuable information about variability of renewable water resources. The 48-year investigation carried out in a small agricultural catchment of the Zagożdżonka River located in centre of Poland, characterized by mean precipitation of 611 mm/a and average runoff of 106 mm/a, indicate a decreased trend in runoff at the probability level of 95%. To confirm this finding further analyses are suggested.

Three-year hydrological investigation and monitoring in two catchments, Zagożdżonka and Zwoleńka, allowed the researchers to establish flow duration curves for both catchments and to indicate factors influencing differences in the FDCs.

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