Long-term Changes in Runoff from a Small Agricultural Catchment

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Abstract: River runoff is an important indicator of environmental changes, which usually include climate and/or land use changes, and is also the basis of catchment water management. This study presents results of monitoring and analysis of 48-year precipitation and runoff from a small agricultural catchment located in central Poland. No land use changes in that period have been reported. Mean monthly distributions of precipitation and runoff for the long-term period showed that July was the wettest month in respect of precipitation and a drier one in respect of runoff, averaging 12.9% and 5.2% of their annual values, respectively. To evaluate the trend of three annual hydrometeorological parameters, i.e. precipitation, runoff and runoff coefficient, the Mann-Kendall test was applied. It indicated no trend in respect of precipitation, and decreasing trends of runoff and runoff coefficient at a 95% level of significance. Linear approximation of the annual runoff values indicated a decrease in runoff of ca. 1.2 mm per year for the analysed period. A few other functions were also used for better approximation of runoff data.

Keywords: climate change; Poland; runoff variability; small watershed; trend analysis

Changes in land use, population density and climate cause spatial and temporal changes in river runoff, called also renewable water resource. For better understanding of these changes and for effective management of water resources, hydrological investigations in river catchments are carried out around the world. A special case of the investigation is the study of hydrological processes in site-specific, small catchments (Rodier 1976; Amatya & Trettin 2011; Mitchell *et al.* 2001). Some of them are focused on presenting the effect on changes in the catchment response caused by land use (Kostadinov & Mitrovic 1994; Banasik *et al.* 1999; Endale *et al.* 2006; Garbrecht 2008; Kliment & Matoušková 2008) or by climate changes (Fernandez & Garbrecht 1994; Keim *et al.* 1995; Holko *et al.* 2006; Pekarova *et al.* 2010), and others provide data for the testing of mathematical models of hydrological processes or form a base for the understanding of complex hydrological processes (Kovář & Kadlec 2009;

Beven 2010; Herrmann *et al.* 2010; Sikorska & Banasik 2010; Warmerdam & Stricker 2010).

The Zagożdżonka River, located in the centre of Poland, is presented to identify the mean annual distribution of precipitation and runoff as well as to determine trends in the annual values of hydrometeorological parameters.

MATERIAL AND METHODS

Location and characteristics of the investigated area

The Zagożdżonka catchment (Figure 1) is a small lowland catchment, with dominant agricultural use, located in central Poland, about 100 km south of Warsaw. The Zagożdżonka River is the left tributary to the Vistula River with its outlet (51°39'28''N; 21°29'13''E) near the town of Kozienice. Hydrological field investigations of the Zagożdżonka River,
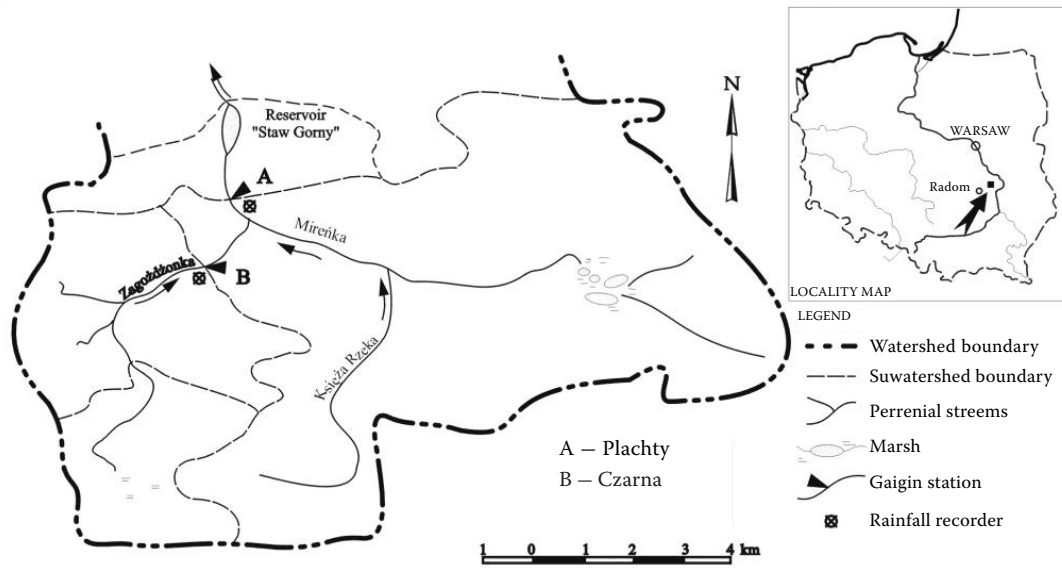
Figure 1. Locality map of the Zagożdżonka catchment and gauging stations

at Płachty (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 Sciences since 1962. Daily values of precipitation and discharge were taken for analysis from the period of 48 hydrological years (1963–2010). In the initial period, the river water stages were recorded by an observer who read the staff gauge three times a day, except flood periods when reading was usually carried out each hour. Since 1980 the monitoring of the river water stages was carried out with the use of a mechanical water stage recorder, and since the middle of the last decade of the previous century with the use of an electronic system for data recording, logging and transmitting. In recent periods,

the traditional reading of the staff gauge once a day has continued for checking the records and eliminating possible errors. For precise estimation of the river flow a rating curve has been established and verified at least once a year based on hydrometric measurements (BYCZKOWSKI 1999) conducted ca. 10–12 times a year. A view of this natural channel gauging station at Płachty is shown in Figure 2 and a view of the meteorological site at Czarna is in Figure 3.

The catchment area at the Płachty gauging station is 82.4 km^2. The lowland catchment of the Zagożdzonka River has topography typical of this part of Poland. The mean elevation of the catchment is about 163 m above sea level, and

Figure 2. View of the stream gauge station at Płachty (the photo is looking downstream)

Figure 3. Meteorological gauging station at Czarna in Zagożdżonka catchment
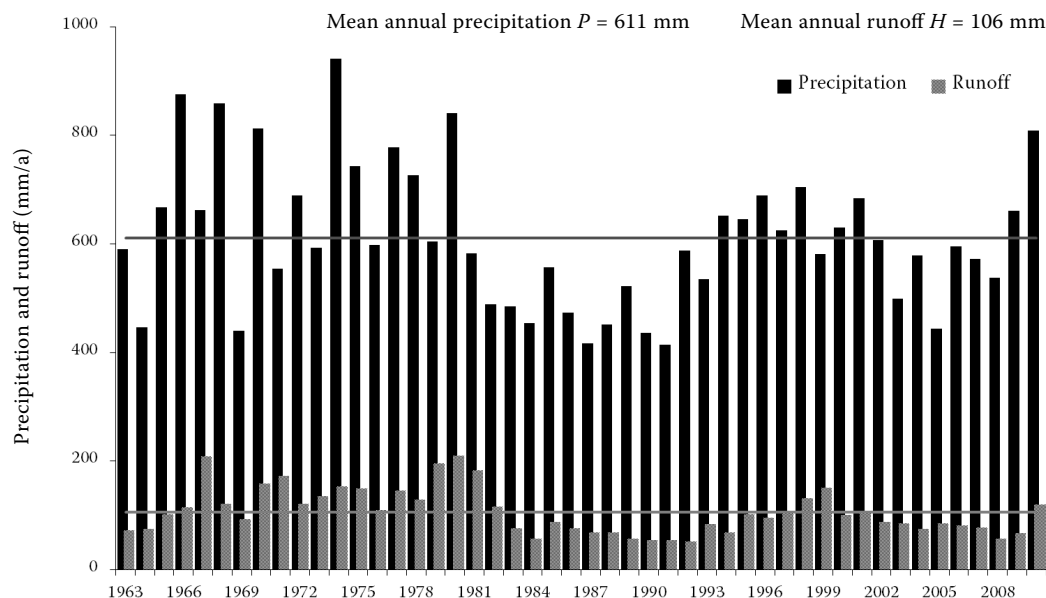
Figure 4. Annual precipitation and runoff depths for the Zagożdżonka catchment upstream of the Płachty gauge station for the hydrological years 1963–2010

the absolute relief is 37.0 m, i.e. from 147.5 to 184.5 m a.s.l. (upstream of A, Figure 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 outflow from the catchment, constitute a significant part of the area, i.e. 19.8 km² upstream of the Płachty gauging station.

Land use is dominated by arable land (small grains and potatoes), which take up 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 hydrometeorological service (IMGW) for the nearest rain gauge, 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 (the ratio of runoff to precipitation) for the area of the Płachty gauging station range from 0.088 (1992) to 0.320 (1979), with the mean value of 0.173. Annual values of precipitation and runoff are shown in Figure 4. Statistical characteristics of the analysed series are presented in Table 1.

Table 1. Main parameters of statistical series of precipitation, runoff and runoff coefficient for Zagożdżonka catchment at the Płachty gauge station for the period of 48 years (1963–2010)

Characteristics of the annual value	Mean value	SD	Relative SD	Skewness
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

SD – standard deviation

RESULTS AND DISCUSSION

Mean monthly distribution of precipitation and runoff in the 48-year period

Mean monthly distributions of precipitation, runoff and discharge for the period of 48 years are represented in Figure 5. One can see from data presented in Table 2 and Figure 5 that in respect of mean long-term precipitation, the wettest month is July with rainfall depth of 78.7 mm, i.e. 12.9% of the annual value, and the driest one is January with the equivalence of rainfall and snowfall depth of 31.6 mm, i.e. 5.2% of the annual value. In respect of mean long-term runoff, the wettest month is March with runoff depth of 15.5 mm, i.e. 14.7% of the annual value and the driest one is July with runoff depth of 5.4 mm i.e. 5.1% of the mean annual runoff.

Trend analysis of annual precipitation, runoff and runoff coefficient

To evaluate the trend of the three parameters, the Mann-Kendall test was selected as it is simple to use and it is often applied for climatological and hydrological trend analysis (Hipel & McLeod 1994; Khambhammettu 2005; Kundzewicz *et al.* 2005; Hamed 2008; Sahooa & 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 monotonic trends in time series data. One benefit of this test is that the data does not need to conform
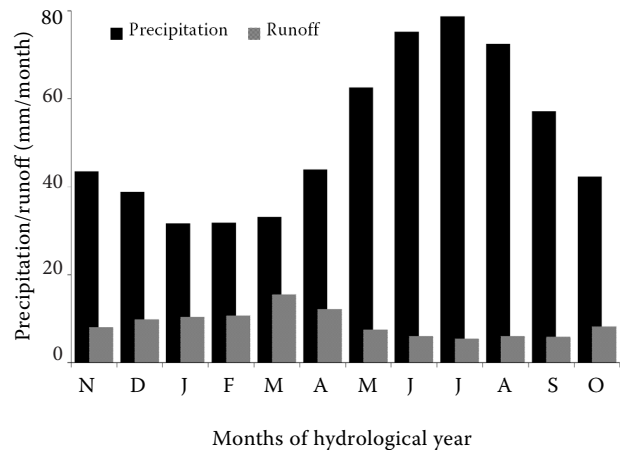

Figure 5. Mean annual distribution of precipitation and runoff in the Zagożdżonka catchment at the Płachty gauge station for the period 1963–2010

to any particular distribution. The data values are evaluated as ordered time series. Each data value is compared with 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 a 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, ... 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 the following formula:

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

Table 2. Monthly and annual values of precipitation and discharge in the Zagożdżonka River at the Płachty gauge station in the period of 1963–2010

Period	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX	X	Annual
Precipitation, *P*													
P (mm)	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, *SQ*													
SQ (m³/s)	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, *H*													
H (mm)	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

where:

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

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 (Кнамвнамметтu 2005). The Mann-Kendall statistics *S* for the analysed parameters, computed according to Eq. (1) and (2), are given in Table 3.

Based on the normalised test statistic *Z*, computed from the following formula (i.e. Węglarczyk 2010):

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

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

$$\text{VAR}(S) = \frac{1}{18}\big(n \cdot (n-1) \cdot (2n+5)\big) \qquad (4)$$

The probability, associated with the normalised test statistic *Z*, was computed using the Microsoft Excel function NORMSDIST. The computed values of normalised test statistic *Z* and probability are given in Table 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, no trend was detected in the case of 48 years of annual precipitation values. Both for the series of annual runoff depths and annual runoff coefficients decreased trends were detected at the probability level of 95% (Table 3). The variation of annual runoff with time is discussed in the next chapter.

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

To analyse the variation of annual values of runoff from the Zagożdżonka catchment at the Płachty gauge station with time, the relations of two types were selected. The first one was composed of three commonly used relationships, i.e.:
linear trend:

$$y = a + bt \qquad (5)$$

periodic cycle

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

and linear trend with periodic cycle

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

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

As the annual values of runoff from 1963–2010 are higher in the first part of the period with a drop at the beginning of the 1980s (Figure 4), the other two relationships of runoff versus time are also presented, one from a group of transition functions and the other from a group of peak functions. To estimate the parameters of the earlier and later functions the TableCurve 2D software (Systat Software Inc., 2002) was used. In the case of the later functions the best fit functions from both groups were selected. The following functions were selected:
from the set of transition functions, the Log Normal Cumulative function:

Table 3. Mann-Kendall trend results (trend at 95% level of significance)

Characteristics	No. of data	Range of the values	Mann-Kendall statistics *S*	Normalized test statistics *Z*	Probability	Trend
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

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

and

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

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

where:

erf(...) – error function

erfc(...) – complementary error function

a, *b*, *c*, *d*, and *e* – estimated parameters, by the Table-Curve 2D software (Systat Software Inc., 2002), of Eq. (8) and (9) (*a* – intercept in mm; *b* – tran-

sition height in Eq. (8) and amplitude in Eq. (9), both in mm; *c* – transition centre in Eq. (8) and centre in Eq. (9), both as year; *d* – shape parameter in Eq. (8) (–) and width in Eq. (9) (year); *e* – shape parameter (year).

Parameters of Eq. (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 4. The equations are also shown in Figure 6 and 7.

The correlation coefficient of the linear relationship (Eq. (5)) compared with the critical one confirms the significance (at the level of 95%) of the decreasing trend of annual runoff, which was ascertained earlier by the Mann-Kendall test. The correlation of annual runoff with time (expressed as hydrological years of the period 1963–2010), measured by determination coefficient (Table 4, column 4), becomes stronger for the periodic cycle (Eq. (6) – no trend included) and for a linear trend with the periodic cycle (Eq. (7)). Parameters of both equations containing the trend element (i.e. Eq.

Table 4. Results of the analysis of temporal variation in runoff with various statistical relationships

Temporal variation	Eq. No.	Parametres	Determination coefficient, r^2	Standard error of estimation
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)	$a = 83.0$ $b = 56.3$ $c = 1982.0$ $d = -5.88\text{E-}05$	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

a, *b*, b_1, b_2, *c*, *d*, *e*, – estimated parameters of the Eqs (5)–(9)
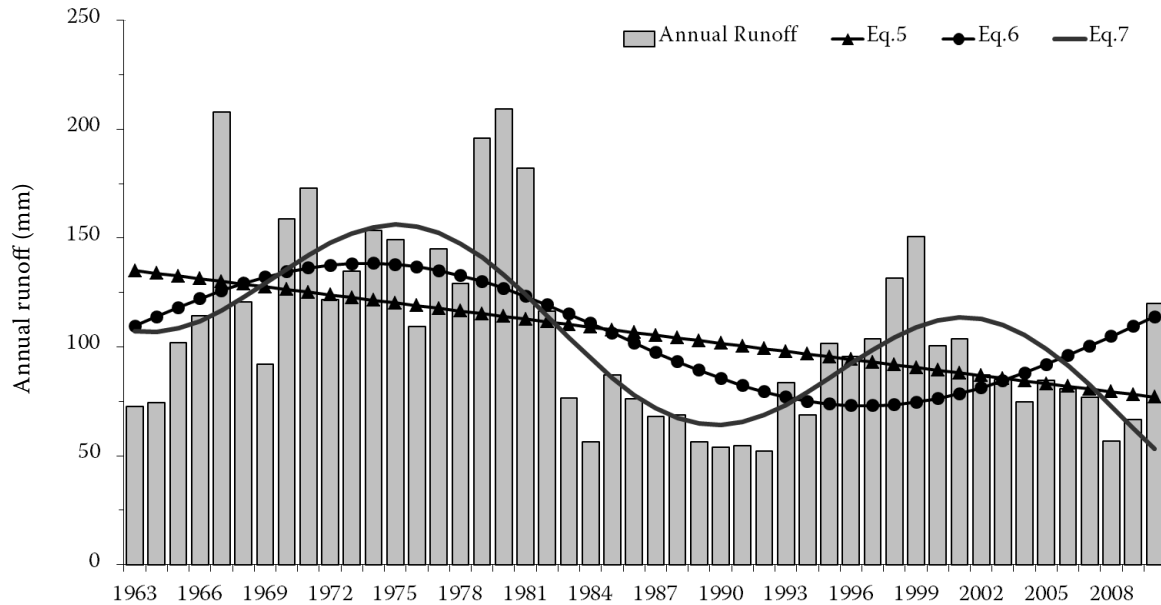
Figure 6. Approximation Eqs (5)—(7) for the annual runoff of Zagożdżonka catchment at the Płachty gauge station for the period 1963–2010

(5) and (7)) indicate the mean annual decrease in runoff of 1.24 mm and 1.64 mm for Eq. (5) and (7), respectively. The respective standard errors of both parameters are 0.403 mm and 0.358 mm. It is worth mentioning that a previous analysis of the runoff of the period of 37 years, i.e. from 1963 to 1999 (Byczkowski *et al.* 2001), also documented a significant decreasing trend of annual runoff with the decrease of 1.36 mm per year.

The relatively high values of determination coefficients for the last two relationships (Eq. (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 the 1980s (see parameter c in Eq. (8) and $c + d/2$ in Eq. (9)) may also indicate the existence of causes influencing the annual runoff. A similar drop of the warm half-year runoff in small forested
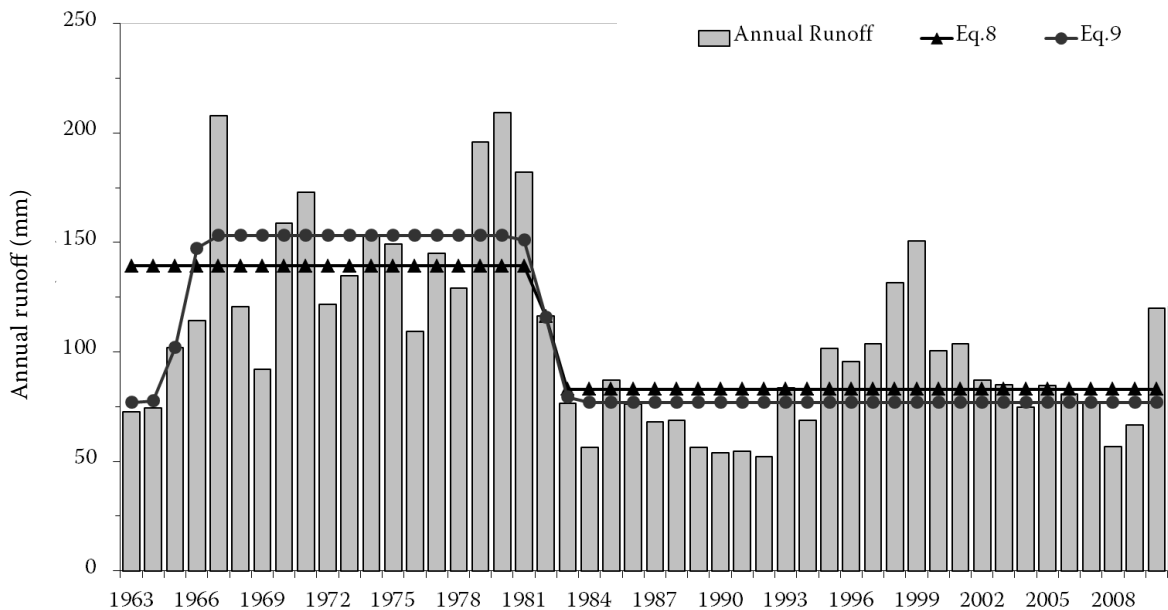

Figure 7. Approximation equations 8 and 9 for the annual runoff of Zagożdżonka catchment at the Płachty gauge station for the period 1963–2010

catchments at the beginning of the 1980s was found by Pierzgalski & Tyszka (2005). Further analysis should consider additional potential causes of the runoff decrease such as:

– meteorological parameters (i.e. air temperatures, evapotranspiration),

– land cover (i.e. crop yields).

To confirm the finding, further analysis is needed, in which also other rain and river gauges, located in the region, will be taken into account, as well as limitations of the Mann-Kendall test (DNR 2004) will be considered.

As no stream engineering works in the catchment have been reported, an increase of the analysed sample, i.e. to extend the period of observation and/or to include an earlier period into the analysis by identifying earlier annual runoff values, should help in finding the causes of the runoff decrease.

CONCLUSIONS

Results of long-term hydrological investigations provide very valuable information about the variability of renewable water resources. The 48-year investigation carried out in a small agricultural catchment of the Zagożdżonka River located in the centre of Poland, characterized by mean precipitation of 611 mm/a and average runoff of 106 mm/a, indicated no trend in respect of precipitation, and decreasing trends of runoff and runoff coefficient at a 95% level of significance. Linear approximation of the annual runoff values indicated a decrease in runoff of ca. 1.2 mm per year for the analysed period. Mean monthly distributions of precipitation and runoff for the long period showed that July was the wettest month in respect of precipitation and a drier one in respect of runoff, averaging 12.9% and 5.2% of their annual values, respectively.

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