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Long-term variability of runoff from a small agricultural catchment of the North Masovian Lowland

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Abstract: Changes of land use, population and climate cause spatial and temporal changes in renewable water resources. For better understanding of the changes and effective management of water resources, hydrological investigations in river catchments are carried out around the world. A special investigation involves a study of hydrological processes in small site-specific catchments. The aim of the study is to analyse three characteristic river flows of a small lowland river on the basis of field surveys over two multiannual periods and to evaluate the applicability of indirect methods for determining characteristic flows in the catchment. Hydrological studies in the small agricultural catchment of the Mławka River, located in the Mławka Hills mesoregion, a part of the North Mazovian Lowland macro-region, have continued since 1966. The recorded data were used to determine daily flows and selected characteristic flows for multiannual periods of 1966–1990 and 1991–2020. To determine characteristic flows with indirect methods, three regional formulae and isorea methods were used. The study showed a decrease in renewable water resources over the period. In the multiannual periods, the average flow at the gauge station of Mławka River decreased by 15.6%. The outflow coefficient decreased from 0.303 to 0.265. The minimum annual flows also decreased by 29.1% and annual maximum flows showed an average increase by 19.7%. The use of indirect methods to determine the mean flow yielded results that converged with those from the second multiannual period.

Keywords: agricultural watershed, climate change, flow decrease, hydrological characteristics, land use change, renewable water resources

INTRODUCTION

Fluvial flow characteristics are important indicators of the state of water resources. They also provide a basis to design water management facilities, such as weirs, reservoirs or intakes (Stachý and Fal, 1986; Stachý, 1990; EA, 2020; Muhammed, Mustafa and Kolerski, 2021; Ozga-Zieliński and Walczykiewicz, 2022). Their determination in small catchments, most of which are not covered by the state hydrological monitoring network, is limited to the use of indirect methods, among which empirical formulae are very popular (Stachý, 1986; Wilson, 1990; Byczkowski, 1999b; Grandry *et al.*, 2013). The variability of flows in small catchments, which are susceptible to changes in use, climate, and local water abstraction for irrigation, makes the accuracy of indirect method results dubious (Chen *et al.*, 2020). Uncertainty in the determination of flows increases when smaller catchments are considered. The reason is the possible periodic poor recharge of the watercourse with groundwater due to fluctuations of the latter (Mitchell *et al.*, 2001; Tramblay *et al.*, 2020; Rutkowska *et al.*, 2022). The few long-term studies carried out in small catchments help to determine the desired hydrological characteristics and to verify indirect methods (Banasik *et al.*, 2022).

The study presents three hydrological characteristics important in the engineering practice: mean flow based on annual maximums (*SWQ*), mean flow based on annual averages (*SSQ*), and mean flow based on annual minimums (*SNQ*). These are determined using multiannual hydrological surveys carried out within the water gauge profile of a small lowland river, outside the official IMGW monitoring network (IMGW – Institute of Meteorology and Water Management). They have been compared with results of two indirect methods applied to each characteristic.

The aim of the study is to investigate: (i) whether *SWQ*, *SSQ* and *SNQ* characteristic flows and corresponding specific discharges of the Mławka River at the Mławka VI gauge changed significantly in the considered period 1966–2020, divided into two multiannual periods of 1966–1990 and 1991–2020; and (ii) whether the application of indirect methods to determine the hydrological characteristics, as related to specific discharges, produces convergent results with those of the current multiannual period. The period of 1991–2020 is considered as representative for the current climatic situation (IMGW-PIB 2021b).

MATERIALS AND METHODS

CATCHMENT CHARACTERISTICS

The study examines flows in the Mławka River, the left tributary of the Wkra River at the Mławka VI gauging profile. It closes the catchment area of 66.2 km^2 located approx. 115 km north of Warsaw. According to the physical-geographic division, it is located at the Mława Heights which are part of the North Masovian Lowland macro-region. The location of the Mławka VI gauging profile on the Mławka River is shown in Figure 1. According to the administrative division, the study area is located on the border of the Mazowieckie and Warmińsko-Mazurskie provinces, in Działdowo and Mława districts. Thus, it constitutes a transition zone between the Mazurian Lake District and the Mazovian Lowland.

In 1991–2020, the average annual precipitation at the nearest meteorological station in Mława, approximately 8 km south of the catchment centre, was 562 mm (IMGW-PIB 2021b). Months with the highest precipitation were July, June and August, with average precipitation of 76, 68 and 57 mm respectively, and months with the lowest precipitation were February and March, 29 and 32 mm respectively. The number of days with precipitation ≥10 mm was 13 per year on average, and the months of June–August included 6.3 such days. A daily precipitation of ≥50 mm occurred on average once every 6 years, and in the multiannual period of 1991–2020 such an event occurred twice in September and once in June, July and October. A similar average annual precipitation of 565 mm for the catchment was listed in the Hydrological Atlas of Poland based on measurement data in 1951–1970 (Stachý, 1987). In 1991–2020, the average daily temperature was 8.2°C and in summer months of June, July and August, the monthly average temperatures were 16.6, 18.7 and 18.3°C, respectively, whereas in winter months, December, January and February, –0.5, –2.3 and –1.2°C, respectively (IMGW-PIB 2021).

While the precipitation data given above indicate relatively constant mean annual precipitation for the given multiannual periods, detailed IMGW data indicate statistically significant increase in the mean annual temperature of 0.29°C per 10 years (1951–2020) for Poland as a whole and 0.30°C per 10 years for lowlands and lake districts (IMGW-PIB 2021a). The same can also be applied for the Mławka River catchment under consideration.

In the catchment area, the main soil types include brown soil (76% of catchment area), podzolic soil (11%) and peat and marshy soils (7%). Considering soil layer type and grading, a distinction is made between light loamy sands (60% of

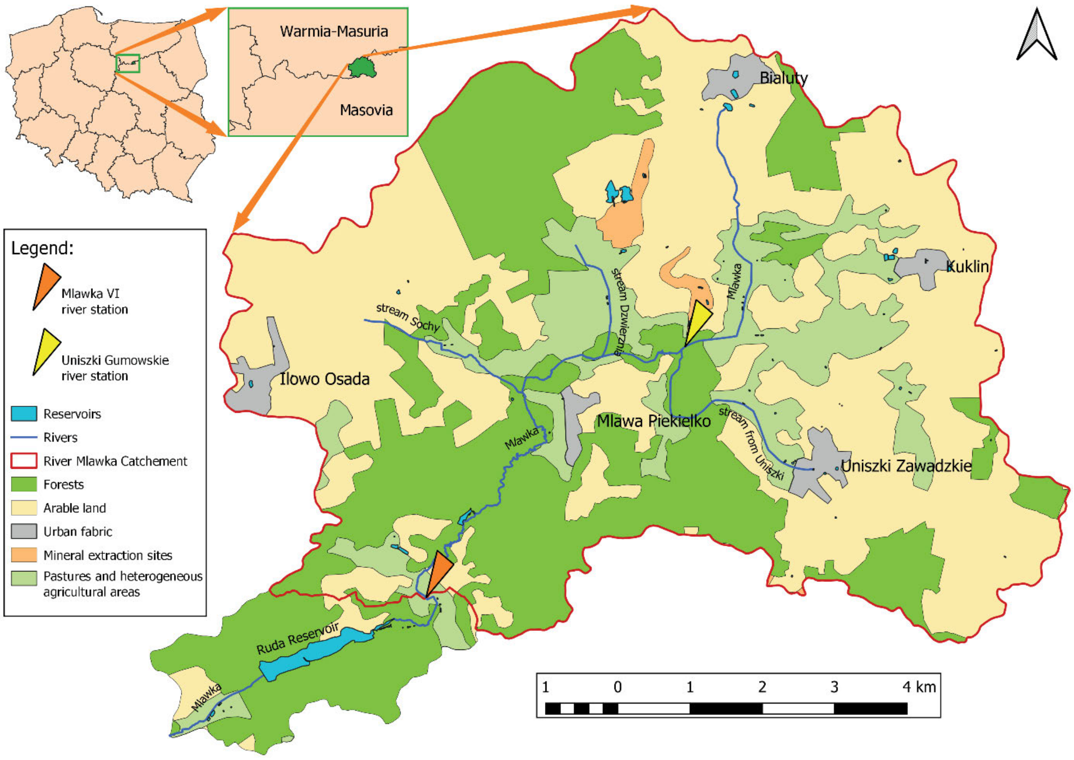

Fig. 1. Mławka River catchment and the location of the Mławka VI river station; source: own study based on MPHP10k and Corine Land Cover 2018

catchment area), loose sands (22%), loamy sands (11%), and low peats (7%). The catchment of the Mławka River is a lowland catchment with a terrain gradient of Δ*H* = 54.2 m (191.7–137.5) and Kajetanowicz's slope of 6.7 m·km^{-1} (Szymczak, 1993; Krężałek, 2018). The main land is arable. In 1992–2018, in the catchment, the share of arable land decreased from 64 to 50%, whereas in the same period forest increased from 23 to 33%. A detailed summary of land use and other catchment characteristics is included in Table 1.

Table 1. Main characteristics of the Mławka catchment upstream of the Mławka VI station

Catchment characteristics	Values
Location of the gauging station	53°08'55.4" N; 20°19'59.0" E
Area – *A* (km^2)	66.2
Height difference between maximum and minimum elevation in the catchment – Δ*H* (m)	54.2 (191.7–137.5 m a.s.l.)
Mean catchment slope – *Ψ* (m·km^{-1})	6.7
Ratio of land use in the catchment in the years 1992 and 2018 (–)	
a) forests	0.23 => 0.33
b) arable land	0.64 => 0.50
c) pastures and heterogeneous agricultural areas	0.09 => 0.13
d) others (settlements, wasteland, mineral extraction sites)	0.04 => 0.04

Source: own study.

Photo 1. Mławka VI gauging station (phot.: *K. Karpińska*)

STUDY METHODS

A direct method to estimate characteristic discharges

Measurements of water levels on the Mławka River in the Mławka VI profile, shown in Photo 1, were carried out by the State Hydrological and Meteorological Institute in 1947–1956. In 1966, observations were resumed by the Institute of Technology and Life Sciences – National Research Institute (formerly Institute of Land Reclamation and Grassland Farming) located in Falenty, Poland. The measurements have continued until today. In the initial period, water levels were recorded by an observer from a staff gauge once a day, and during level fluctuation periods, several times a day, as recommended to the Polish hydrological service (Pasławski, 1973; Byczkowski, 1999a). In 1976, a trapezoidal overflow was built in the gauging profile, stabilising the zero-flow condition and thus increasing the accuracy of measurements. Moreover, a mechanical limnigraph was installed for continuous recording of water levels on a weekly basis. Since 1996, water levels have been monitored using electronic pressure sensors and recording systems at 10-minute intervals. Daily water level readings by an observer have been provided to control the correct operation of the system and the accuracy of status recording.

Hydrometric flow measurements, taken with a hydrometric staff at the water gauge profile about 8–12 times each year, were the basis for establishing the rating curve, i.e. the dependence of flow expressed in m^3·s^{-1} on the water level expressed in centimetres. This relationship, tested and adjusted annually if necessary, was used to determine daily flow values. Based on these, primary main flows were determined for each hydrological year (1 November previous year – 31 October given year) using the following:

- annual mean flow *SQ* (m^3·s^{-1}):

$$SQ = \frac{\sum_1^N Q_i}{N} \tag{1}$$

where: Q_i = daily flows (m^3·s^{-1}): for 1, 2, 3, …, *N*, *N* = number of days in the hydrological year (–);

- minimum annual flow:

$$NQ = \min(Q_1;\ Q_2;\ Q_3; \ldots; Q_N) \tag{2}$$

- maximum annual flow:

$$WQ = \max(Q_1;\ Q_2;\ Q_3; \ldots; Q_N) \tag{3}$$

Multiannual secondary main flows of 1966–1990 and 1991–2020 were determined as follows:

- multiannual average flow *SSQ* (m^3·s^{-1}):

$$SSQ = \frac{\sum_1^n SQ_i}{n} \tag{4}$$

where: SQ_i = annual mean flows (m^3·s^{-1}): for 1, 2, 3, …, *n*, *n* = number of years in the multiannual period considered (–);

- multiannual mean low flow *SNQ* (m^3·s^{-1}):

$$SNQ = \frac{\sum_1^n NQ_i}{n} \tag{5}$$

where: NQ_i = annual minimum flows (m^3·s^{-1}): for 1, 2, 3, …, *n*, *n* = number of years in the considered multiannual period (–);

- multiannual mean high flow *SWQ* (m^3·s^{-1}):

$$SWQ = \frac{\sum_1^n WQ_i}{n} \tag{6}$$

where: WQ_i = annual maximum flows (m^3·s^{-1}): for 1, 2, 3, …, *n*, *n* = number of years in the multiannual period considered (–).

The above-mentioned characteristic flows, both primary and secondary, were determined on the basis of daily flows. Average flows over a longer period, e.g. a year or multiannual period, are a measure of water abundance. Another measure of the abundance is the runoff over a defined period, usually expressed in millimetres per year. The relationship between these parameters is as follows:

$$H = 31.5 \cdot 10^3 \frac{SQ}{A} \tag{7}$$

where: H = runoff depth (mm·y^{-1}), 31.5·10^3 = conversion factor, SQ = annual mean flow (m^3·s^{-1}), A = catchment area (km^2).

In the engineering practice, in some situations – especially while designing hydraulic and certain road structures (e.g. weirs, bridges, culverts) – maximum flows of a certain exceedance probability are used. They are determined based on instantaneous flows. Hence, the annual maximum flows given here (WQ_i) should be adjusted accordingly before their possible use in designing.

In addition to the above-mentioned three characteristic flows (i.e. medium, low, and high), the main flows also include the middle (median) flow, called the ordinary flow. Due to the lack of empirical formulae for determining SWQ, further analysis determines the ordinary flow based on the annual maximum ZWQ, i.e. the maximum flow with an empirical exceedance probability of 50%:

- multiannual ordinary high flow ZWQ (m^3·s^{-1}):

$$ZWQ = \text{median}\ (WQ_1;\ WQ_2;\ WQ_3; \ldots ; WQ_n) \tag{8}$$

where: WQ_i = annual maximum flows (m^3·s^{-1}): for 1, 2, 3, …, n, n = number of years in the multiannual period considered (–).

Indirect methods to estimate characteristic discharges

Indirect methods for determining characteristic flows are used when direct methods based on measurements and field surveys are not possible. In this study, two groups of indirect methods were applied. They used regional empirical formulae and maps of characteristic unit runoffs to prove the compliance of their application with results of measurements.

These are the only methods available for determining mean and mean low flows and the maximum flow with the exceedance probability of 50% (corresponding to ZWQ) over a multiannual period in catchments that have not been monitored in the region. Hence, an attempt was made to apply them, even though they were based on measurement data collected by the national hydrological service in the beginning of the second half of the previous century.

1) Characteristic flows determined based on regional empirical formulae.
   a) Iszkowski's formula with runoff coefficient according to Byczkowski (1999b) for the multiannual average flow:

$$SSQ = 0.0317cPA \tag{9}$$

where: SSQ = mean multiannual flow (m^3·s^{-1}), c = regional runoff coefficient (–), P = mean annual precipitation in the catchment (m), A = catchment area (km^2).

   b) Stachý's formula (as cited in Byczkowski (1999b)) for the mean low flow over the territory of the country excluding the Carpathian Mountains:

$$SNQ = 4.068 \cdot 10^{-4} \cdot A^{1.045}\ SSq_p^{0.957}\ i_r^{\ 0.111}\ (1 + Jez)^{0.234} \tag{10}$$

where: SNQ = average low flow (m^3·s^{-1}), A = catchment area (km^2), SSq_p = multiannual average specific outflow originating from underground recharge, determined from the map included in the Hydrological atlas of Poland (Stachý, 1987) (dm^3·s^{-1}·km^{-2}), i_r = slope of a stream (m·km^{-1}) calculated from formula (11), Jez = dimensionless lake density index (–) calculated using equation (12).

$$i_r = \frac{\Delta W}{L + l} \tag{11}$$

where: $\Delta W = W_g - W_d$ = difference in watershed height at the point of intersection with the dry valley axis W_g (m a.s.l.) and the height of the design section enclosing the watercourse W_d (m a.s.l.), $L + l$ = length of the watercourse L including the dry valley l (km).

$$Jez = \frac{\sum_{i=1}^{k} A_{j_i}}{A} \tag{12}$$

where: A_{ji} = catchment area of the i-th lake (km^2) whose area s_i is equal to or greater than 1% of its catchment area ($s_i \geq 0.01A_{ji}$), k = number of lakes in the watercourse catchment (–).

   c) Stachý's and Fal's formula (1986) for the maximum flow with the exceedance probability of 50%, corresponding to ZWQ:

- regional for the eastern lowland-lake area:

$$ZWQ = 1.495 \cdot 10^{-5} A^{0.76} H_1^{2.10} (1 + Jez)^{-1.49} (1 + B)^{-1.36} \tag{13}$$

nationwide adapted for the eastern lowland-lake area:

$$ZWQ = 2.814 \cdot 10^{-4} A^{0.98} H_1^{1.06} \varphi^{0.53} i_r^{0.05} \Psi^{0.40} (1 + Jez)^{-1.66} (1 + B)^{-0.67} \tag{14}$$

where: ZWQ = maximum flow with the exceedance probability of 50% (m^3·s^{-1}), A = catchment area (km^2), H_1 = maximum daily rainfall with a probability of exceedance of 1% (mm), Jez = dimensionless lake density index (–) calculated using equation (12), B = catchment swamp index (–) calculated using equation (15), φ = runoff coefficient for maximum annual flows (φ = 0.32 determined according to the soil composition in the catchment area: clay sand – 71%, loose sand – 22% and peat – 7%), i_r = slope of a stream (m·km^{-1}) calculated using formula (11), Ψ = catchment slope (m·km^{-1}) calculated according to Kajetanowicz's formula (16).

$$B = \frac{\sum_{i=1}^{k} A_{b_i}}{A} \tag{15}$$

where: A_{bi} = area of a single marsh (bog) (km^2), k = number of marshes in the catchment (–).

$$\Psi = \frac{W_{\max} - W_d}{\sqrt{A}} \tag{16}$$

where: $W_{\max}$ = height of the highest point of the catchment (m a.s.l.), W_d = height of the design section enclosing the watercourse (m a.s.l.).

2) Characteristic flows determined using area distribution maps for unit runoffs.

A general formula was used to determine characteristic flows of *SSQ*, *SNQ* and $Q_{max,50\%}$:

$$Q = qA \tag{17}$$

where: Q = characteristic flows, respectively *SSQ*, *SNQ*, $Q_{max,50\%}$ ($m^3 \cdot s^{-1}$), q = specific discharges, respectively *SSq*, *SNq*, $q_{max,50\%}$ ($m^3 \cdot s^{-1} \cdot km^{-2}$), A = catchment area (km^2).

Values of individual parameters used for the calculations according to the above formulae and according to the isorea methods were established based on the Hydrological Atlas of Poland and a 1: 25,000 topographic map. Results are presented in Tables 1 and 2.

Table 2. Characteristics of the study catchment used in the formulae 9–17

Catchment characteristics	Value
Height difference between the crossing between dry valley axis and catchment boundary and minimum elevation in the catchment – ΔW (m) [Wg–Wd] (m a.s.l.)	41.0 [178.5–137.5]
Length of the river with dry valley – $L + l$ (km)	12.0
Slope of the stream – i_r ($m \cdot km^{-1}$)	3.42
Runoff coefficient for maximum annual flows (determined according to soil composition in the catchment area: loamy sand 71%, loose sand 22%, and peat 7%)	0.32
Lake density index – *Jez* (–)	0.00
Swamp index – *B* (–)	0.00
According to the Hydrological Atlas of Poland (Stachý, 1986; Stachý, 1987)	
Mean annual precipitation – *P* (mm):	
a) according to the atlas (sheet 10) for the period 1951–1970	565
b) according to IMGW-PIB (2022) for Mława City in 1991–2020	562
Maximum daily precipitation with the exceedance probability of 1% (mm) (sheet 14)	78
Average low unit runoff – *SNq* ($dm^3 \cdot s^{-1} \cdot km^{-2}$) (sheet 61)	1.2
Average unit runoff – *SSq* ($dm^3 \cdot s^{-1} \cdot km^{-2}$) (sheet 56)	4.7
Maximum unit runoff with the exceedance probability of 50% – $q_{max,50\%}$ ($dm^3 \cdot s^{-1} \cdot km^{-2}$) (sheet 59)	45
Average unit runoff of underground origin – SSq_p ($dm^3 \cdot s^{-1} \cdot km^{-2}$) (sheet 65)	1.3
According to Byczkowski's table (Byczkowski, 1999)	
Runoff coefficient – *c* (–) (value as for Wkra River after Cieksyn)	0.25

Source: own elaboration.

RESULTS AND DISCUSSION

The renewable water resources of the catchment characterised by the mean annual flow or runoff depth, as well as other characteristics, such as low and maximum flows, vary from year to year depending on meteorological conditions. In the longer term, they also depend on climate and land use changes in the catchment. The results of hydrological parameter calculations discussed are presented for the two multiannual periods of 1966–1990 and 1991–2020 against the basic climatic (precipitation and temperature) and land use characteristics. According to data in Table 3 and Figure 2, it can be seen that the average annual runoff decreased from 170.6 mm to 143.9 mm, respectively in 1966–1990 and 1991–2020, i.e. by 15.6% [(26.6/170.6)·100%].

Table 3. Annual runoff in the Mława catchment in 1966–2020

Period	H_m	*SD*	Range of runoff depth		Extreme year	
			min	max	dry	wet
	mm					
1966–1990	170.6	34.0	116.1	243.8	1966	1980
1991–2020	143.9	34.6	85.1	212.5	2016	1999
1966–2020	156.1	36.6	85.1	243.8	2016	1980

Explanation: H_m = mean annual runoff depth, *SD* = standard deviation.
Source: own study.

Assuming the average annual precipitation in the studied catchment to be 565 and 562 mm (Stachý, 1987; IMGW-PIB, 2022) and based on the aforementioned runoffs in the two multiannual periods, the average runoff coefficient (*H*/*P*) is 0.303 and 0.256, respectively. This confirms the decrease in renewable resources with practically unchanged average precipitation in the considered multiannual periods. This may be due to increased evapotranspiration caused by both an increase in the mean annual air temperature by about 0.30°C per 10 years for this region of Poland in the period of 1951–2020, and an increase in the proportion of forested land from 23 to 33% of the catchment area in 1992–2018. This hypothesis is also supported by the results of studies conducted in other small catchment areas (Hejduk *et al.*, 2021; Krajewski *et al.*, 2021) and other regions (Indarto *et al.*, 2020; Heyi, Dinka and Mamo, 2022).

While analysing the second multiannual period, i.e. 1991–2020, and taking the statistical criterion (Fal *et al.*, 1997) as the boundary of extremely dry and wet years, i.e. in which runoff lies outside the interval (H_m – *SD*, H_m + *SD*; where H_m = mean annual runoff depth and *SD* = standard deviation), it has been found that 2009, 2015, 2016, 2019 and 2020 were extremely dry years, and 1995, 1999, 2002 and 2004 were extremely wet (Fig. 3). The accumulation of wet years at the beginning and dry years at the end of the 1991–2020 multiannual period indicates that the decrease in renewable water resources has continued.

Characteristic discharges estimated on the basis of measurement and computation of the daily time step are presented in Figure 3 and Table 4. The data show that the multiannual average of mean annual (*SSQ*) and minimum annual (*SNQ*) discharges have decreased by 0.056 and 0.043 $m^3 \cdot s^{-1}$ i.e. of 15.6 and 29.1% respectively between the first (1966–1990) and the second (1991–2020) period. There is a decrease of 3.6% in the median of maximum annual discharges (*ZWQ*) and increase of 19.7% in average of maximum annual discharges (*SWQ*) between the two periods.

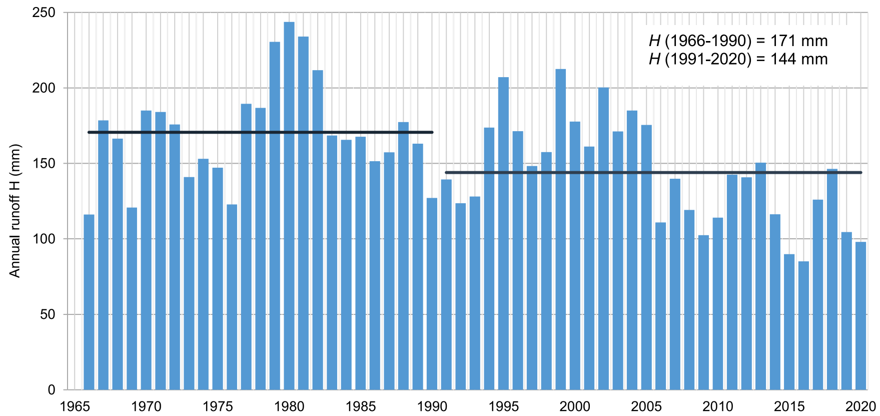

Fig. 2. Annual runoff from the Mławka catchment at the Mławka VI gauge in 1966–2020 and mean annual runoff in periods 1966–1990 and 1991–2020; source: own study

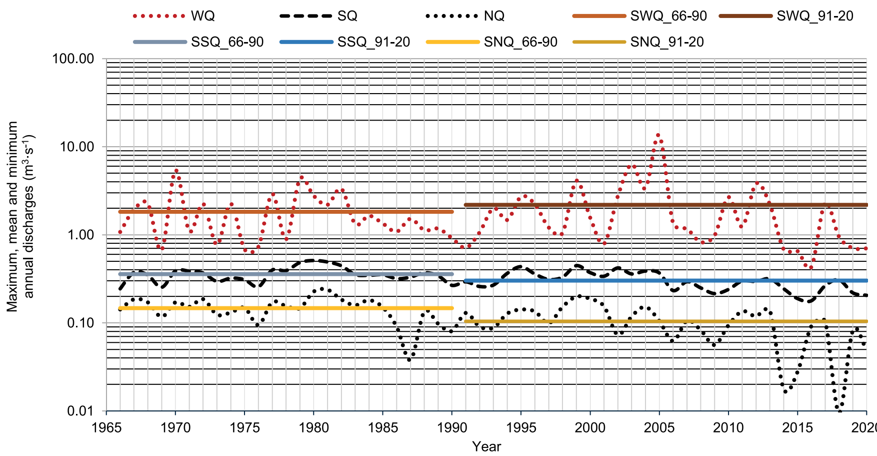

Fig. 3. Maximum, mean and minimum annual discharges (*WQ*, *SQ* and *NQ* respectively) at the Mławka VI river gauge in the period 1966–2020 and multiannual average of maximum (*SWQ*), mean (*SSQ*) and minimum (*SNQ*) annual discharges in the periods 1966–1990 and 1991–2020; source: own study

Table 4. Multiannual average of maximum (*SWQ*), mean (*SSQ*), and minimum (*SNQ*) and median of maximum (*ZWQ*) yearly discharges from the study catchment in the period 1966–2020

Multiannual discharge	Characteristic discharges in the periods ($m^3 \cdot s^{-1}$)			Changes in discharge[1)]	
	1966–2020	1966–1990	1991–2020	ΔQ ($m^3 \cdot s^{-1}$)	%
Average of maximum – *SWQ*	2.021	1.825	2.185	0.360	19.7
Median of maximum – *ZWQ*	1.342	1.342	1.294	–0.048	–3.6
Average of mean – *SSQ*	0.327	0.358	0.302	–0.056	–15.6
Average of minimum – *SNQ*	0.124	0.147	0.104	–0.043	–29.1

[1)] Changes are defined as differences between values in the periods1966–1990 and 1991–2020.
Source: own study.

The statistical significance test applied for the two multiannual average in 1966–1990 and 1991–2020 for *NQ*, *SQ* and *WQ*, indicates that we should reject the null hypothesis of a non-significant difference in the multiannual flows *SNQ* and *SSQ* and no grounds for the rejection in the case of *SWQ*. Cohen's (1988) parameter *d*, determining the effect of the difference between analysed quantities for the *SNQ*, *SSQ* and *SWQ* flows, was 0.96, 0.79 and 0.19, respectively. Thus, these are considered as very strong ($d > 0.80$), strong ($0.50 < d \leq 0.80$) and weak ($d \leq 0.20$) effects.

A similar hydrological study of the Zagożdżonka River of 82.4 km^2, located in the macro-region of the South Mazovian Hills, also showed a decrease in renewable water resources despite equal precipitation in the two multiannual periods (Banasik *et al.*, 2022). The mean flow at the Płachty Stare River gauge decreased by 24% in the 1991–2020 as compared to 1963–1990, with the mean annual runoff depths H = 118 and 89.9 mm, respectively. The minimum annual discharge of *SNQ* decreased by 43% between the multiannual periods.

Table 5 compares *ZWQ* (median of annual highest discharges), *SSQ* (mean of annual mean discharges) and *SNQ* (mean of annual minimum discharges) determined by the direct method, i.e. based on field surveys at the Mławka VI gauge in the period 1991–2020, with corresponding discharges determined by indirect methods, according to the following:

a) empirical formulae – Iszkowski's formula with a discharge coefficient according to Byczkowski for the multiannual mean discharge (*SSQ*), Stachý's formula for the mean low discharge (*SNQ*) and Stachý's and Fal's (1986) formula for the maximum discharge with the exceedance probability of 50%, corresponding to *ZWQ*,
b) maps of the area distribution for unit discharges from the Hydrological Atlas of Poland.

large discrepancies. In the case of *SNQ*, the measured value shows underestimation, while *ZWQ* overestimation. The smallest discrepancies occur when using the Hydrological Atlas of Poland to determine *SNQ* and the empirical formula adapted for the region to determine *ZWQ*.

While determining maximum and minimum flows (*ZWQ* and *SNQ*), differences in results produced by indirect methods are the result of catchment specific features. They may be caused by a higher retention potential (mitigating both surges and lows) than average conditions of the catchment (usually larger) on which the applied formulae and maps were developed. The higher than average retention potential of the Mławka catchment may be due to a significant proportion of forests in the catchment area and the highly meandering shape of the river in its lower section.

Table 5. Comparison of hydrological characteristics estimated with the use of direct method (measurement) in the period 1991–2020 and indirect methods for the catchment area

Multiannual discharges	Discharge estimated with the various methods ($m^3 \cdot s^{-1}$)			Differences between indirect method and measurements			
	measurements	indirect method		$m^3 \cdot s^{-1}$		%	
		A	B	A	B	A	B
Median of maximum – *ZWQ*	1.93[1)]	3.40[2)] 2.89[3)]	2. 98	1.47 0.97	1.05	76.2 50.3	54.4
Average of mean – *SSQ*	0.302	0.295	0.311	–0.007	0.009	–2.3	3.0
Average of minimum – *SNQ*	0.104	0.048	0.079	–0.056	–0.025	–53.9	–24.0

[1)] This is temporary discharge, which was assumed as 1.49 of the daily value based on regression relation for peak discharges of 2007–2020, [2)] by regional formula, [3)] by general formula adapted for the region.
Explanations: A – regional formulae, B – specific discharges acc. to hydrological atlas.
Source: own study.

In the case of high discharges, the comparison of values from indirect methods with measured values showed a significant overestimation of the results. In the case of Stachý's and Fal's formulae, the differences were 1.47 and 0.97 $m^3 \cdot s^{-1}$, and in the case of the value determined from the specific discharge map 1.05 $m^3 \cdot s^{-1}$. Thus, the relative overestimation was 76 and 50%, respectively, using the regional formula and the nationwide formula adapted for the area, and 54% using the specific discharge determined from the atlas.

In the case of mean flows, the comparison of values from indirect methods with measured values showed good convergence. In the case of Iszkowski's formula, the underestimation was 0.007 $m^3 \cdot s^{-1}$, i.e. 2.3%, while in the case of specific discharge values according to the atlas, the overestimation was 0.009 $m^3 \cdot s^{-1}$, i.e. 3.0%.

In the case of low flows, results of indirect methods show an underestimation of the measured values. The application of Stachý's formula shows an underestimation of 0.056 $m^3 \cdot s^{-1}$, i.e. by 54%, while the value determined according to the specific discharge based maps shows an underestimation of 0.025 $m^3 \cdot s^{-1}$, i.e. by 24%.

On the basis of the above data, it can be concluded that the application of indirect methods for the determination of characteristic flows in the Mławka River catchment leads to convergent results with 1991–2020 measurements for *SSQ* mean flows, both using the empirical formula and data from the Hydrological atlas of Poland, while other characteristics show

CONCLUSIONS

1. Hydrological studies continued since 1966 in the catchment of the Mławka River of 66.2 km^2, located in the macro-region of the North Mazovian Lowland, have shown a progressive decrease in renewable water resources in the considered multiannual periods of 1966–1990 and 1991–2020. With a similar mean annual precipitation of about 565 mm in both multiannual periods, the mean annual discharge decreased by 15.6%, i.e. from 170.6 mm to 143.9 mm, respectively in 1966–1990 and 1991–2020. This corresponds to mean *SSQ* flows in the multiannual periods of 358 and 0.302 $m^3 \cdot s^{-1}$, respectively. The runoff coefficient decreased from 0.303 to 0.265. This may be attributed to the increased evapotranspiration caused both by an increase in the mean annual air temperature (by about 0.30°C per 10 years in 1951–2020) in the region and an increase in the proportion of forested land in the catchment by about 10% at the expense of arable land.
2. The low flows in the considered multiannual periods, characterised by the mean flow from annual minimums (*SNQ*), decreased even more significantly by 29.1%, i.e. from 0.147 to 0.104 $m^3 \cdot s^{-1}$. The increase in the multiannual average of the maximum flows (*SWQ*), from 1.825 to 2.185 $m^3 \cdot s^{-1}$ proved to be statistically insignificant.
3. The application of indirect methods to determine characteristic flows in the Mławka River catchment showed convergence

with the results of *SSQ* mean flows measurements in 1991–2020, both using the empirical formula and data from the Hydrological atlas of Poland, as well as large discrepancies in the case of other characteristics. In the case of *SNQ*, the measured value showed underestimation, whereas in the case of *ZWQ* This is presumably a result of the catchment specific features and a higher retention potential, as they mitigate both surges and lows more than average conditions in rather larger catchments for which the formulae and maps were developed.

4. The results indicate a clear variability of hydrological characteristics over time. The decrease in mean flow and mean low flow between the two multiannual periods might be caused by changes of climate and land use. Further research will enable a detailed assessment of the catchment response to intense rainfall as well as long periods without rainfall.

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