INFLUENCE OF THE PRECIPITATION PATTERN ON THE WATER RUNOFF DYNAMICS FROM THE LOESS GULLY IN THE LUBLIN UPLAND (EASTERN POLAND) IN THE YEARS 2003–2022

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Abstract: Over the period 2003–2022, the precipitation and runoff of water from the loess catchment with an area of 1.23 km^2 was monitored. The agricultural catchment, located in Kolonia Celejów (Nałęczów Plateau, SE Poland), is drained episodically, sometimes periodically. It is dissected by a gully system with a density of erosion forms of about 6 km · km^{-2} and it is representative for the loess areas with high gully density. The study aimed to determine the relationship between the precipitation pattern and gully water runoff. In the 20-year measurement series, four multi-year periods with similar annual hydro-meteorological indicators were distinguished. The first four years (2003–2006) predominately of snowmelt runoff, were separated as the nival period. This was followed by a short stable period in 2007–2009, with almost no gully runoff. The next period, the longest (2010–2018), was characterised by relatively mild winters and moderate snowmelt, while numerous summer rainstorms occurred. These mainly generated frequent runoff and surface wash, separating this period as pluvial. The most recent period (2019–2022), variable, was dominated by medium runoff years, with a changing dominant type. However, the contribution of propluvial and pronivial runoff in the gully was found to equalise on a multi-year scale. The observed decrease in the snowiness of winters and lack of intense snowmelt may change these proportions, in favour of propluvial runoff.

Keywords: multi-year weather conditions, gully runoff variability, snowmelt and rainfall runoff, runoff periodically, loess gully

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Introduction

It is thought that loess gullies play an important role in the hydrological balance of river catchments, especially during heavy rainfall. Then they can accelerate surface runoff and transport loess material with mainly silt-sized particles (10–50 μm) from the catchment into river channels (Buraczyński, Wojtanowicz 1974, Rodzik 1981, Maruszczak et al. 1984; Poesen et al. 1996, Verstraeten, Poesen 1999, Poesen et al. 2003, Valentin et al. 2005, Torri et al. 2006, 2012, Sidle et al. 2017, Yang et al. 2019, Chen et al. 2024). Further, gully development also can increase runoff and sediment connectivity between the landscapes (Rodzik 1981, Maruszczak 1986, Zgłobicki 2002, Sidle et al. 2017). Gully network increases the risk of flash flood (Poesen et al. 2003), muddy flood (Gardziel et al. 1998), general flooding (Stolte et al. 2003, Van de Elsen et al. 2003, Yang et al. 2019) and sedimentation in reservoirs (Zgłobicki 2002,

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Rodzik, Janicki 2003, Ionita 2006, Poesen 2011). Gully erosion represents a major sediment-producing process, generating 10–95% of total sediment mass in catchments while gullies often only occupy less than 5% of catchment area (Poesen et al. 2003).

In the literature, descriptions of spectacular erosion-accumulation effects accompanying extreme hydro-meteorological events predominate (Maruszczak, Trembaczowski 1958, Buraczyński, Wojtanowicz 1974, Rodzik 1981, Maruszczak et al. 1984, Maruszczak 1986, Stolte et al., 2003, Sidle et al. 2017, Yang et al. 2019, Chen et al. 2024). However, there is a lack of work presenting the results of long-term recording of gully outflow and concerning the impact of gullies on the water balance of the loess catchment. The determination of the contribution of the different types of runoff, snowmelt and rainfall, is therefore not based on continuous measurements, but on the results of patrol surveys or short-term recordings (Józefaciuk, Karczewski 1991, Furtak, Rodzik 2007, Rodzik et al. 2009). This study aims, therefore, to fill this gap by continuously measuring water runoff over a multi-year period, under different weather conditions, which made it possible to distinguish the types of outflow and analyse them statistically. Such a detailed recording of gully outflow has not previously been presented in the scientific literature. Therefore, the results obtained are unique and allow research to be undertaken using mathematical models. The results obtained can be used for comparisons with other loess areas with gully networks.

The gullies, by definition, have no permanent drainage and no formed channel, while minor runoff can be obstructed by a layer of litter. Gullies with intermittent runoff and a formed channel respond more quickly. Most often, propluvial runoff is generated by dirt roads routed on the slopes, which results in the rapid development of sunken lanes (Ziemnicki, Naklicki 1971, Verstraeten, Poesen 1999, Gardziel, Rodzik 2005). Thus, important for conducting stationary, long-term studies is the selection of a representative, compact gully catchment with a partially formed runoff. Such criteria are met by the gully catchment in Kolonia Celejów, which has a near-square shape with periodic or episodic water runoff. The observation began in 1997, while hydrological and geomorphological measurements were undertaken in 2003 (Rodzik et al. 2009). Continued surveys leave no gaps in data recording, allowing a complete overview of the investigated issues to be gained. After more than 20 years, a long series of measurements was obtained, allowing the separation of several-year periods with similar runoff characteristics. It was initially assessed that the volume and dynamics of surface runoff depends on the rainfall pattern, but is significantly modified by the existing loess catchment retention capacity. Occasionally, studies of gully runoff have been conducted in Poland too, such as in Niemienice near Krasnystaw. It has been shown that, compared to dry loess valleys used agriculturally, runoff from valley gullies occurs infrequently and reaches low values of Mazur and Pałys (1991, 1992). In contrast, measurements of runoff from three gully catchments on the Nałęczow Plateau showed that local conditions (including catchment elongation) can form runoff that differs by an order of magnitude even in neighbouring catchments (Józefaciuk, Karczewski 1991).

The main aim of the study was to determine the relationship between the precipitation pattern and gully water runoff in different weather conditions and in long time scale. In particular, an attempt was made to define the variability and periodicity of the total runoff, as well as its components. A further aim was to evaluate the trend in runoff changes over a multi-year period and the role of snowmelt and torrential rainfall in total water runoff from the gully catchment. An important task of the research undertaken was also to calculate the strength of relationships and to modelling the rainfall-runoff relationship in the gully catchment.

Study area

A small and homogeneous catchment of low hydrological order was chosen for the study, which can be represented for loess areas with a well-developed surface runoff network, consisting of dry valleys and gullies. The studied gully system shows exceptional hydrogeomorphological activity, intensified after intense spring thaws (1996), summer downpours (1997, 1999) and mid-winter thaws (1998, 2000). In addition, the Kolonia Celejów gully catchment has a long measurement series, which is important for determining the conditions and variability of water runoff from the catchment.

The observation began in 1997, while hydrological and geomorphological measurements was undertaken in 2003 (Rodzik et al. 2009). Continued surveys leave no gaps in data recording, allowing a complete overview of the investigated issues to be gained. After more than 20 years, a long series of measurements was obtained, allowing the separation of several-year periods with similar runoff characteristics. It was initially assessed that the volume and dynamics of surface runoff depends on the rainfall pattern, but is significantly modified by the existing catchment retention capacity. In addition, important for conducting stationary, long-term studies is a compact gully catchment in Kolonia Celejów, which has a near-square shape. Early measurements of runoff from three gully catchments on the loess gully areas showed that catchment elongation can form runoff that differs by an order of magnitude even in neighbouring catchments (Józefaciuk, Karczewski 1991).

The studied gully catchment in Kolonia Celejów covers 18% of the catchment area of the Stok Stream, which reaches the Bystra River, a right-bank tributary of the Vistula (Fig. 1). The gully catchment: represents typical features of the environment of the Nałęczów Plateau, a loess region of the Lublin Upland (Rodzik et al. 2009), with the densest network of gullies in Poland (Maruszczak 1973, Gawrysiak, Harasimiuk 2012, Zgłobicki et al. 2021). The site is located on the border of two types of loess relief: (a) with height difference up to 50 m with predominantly dry valley systems and (b) with gradients >50 m with a gullies network (Fig. 1).

These gullies have developed in a uniform Vistulian loess cover, up to a dozen meters thick. The bottoms of the main gullies locally incise into glaciogenic formations: glacial till and fluvioglacial sands, sometimes even reaching the weathering of the so-called siwak, i.e. Paleocene gaizes with lenses of limestone (Harasimiuk, Henkiel 1976). The absolute heights of the catchment area in Kolonia Celejów range from 165 to 213 meters above sea level (m a.s.l.), while relative heights reach up to 50 m. The catchment is dominated by complex, convex-concave, mostly convergent slopes, varying in length from 50 m to 400 m. The average slope of the catchment is 8° and is dominated by the perpendicular field pattern to the axis of the gully and the longitudinal tillage direction. These conditions accelerate the surface runoff formation and the runoff concentration at the bottom of the gully. The maximum length of the runoff is approximately 1500 m and the wave run-up time to the water gauge closing the catchment does not exceed 30 min.

The catchment area includes a branching system of gullies, with a total length of 7.5 km. The

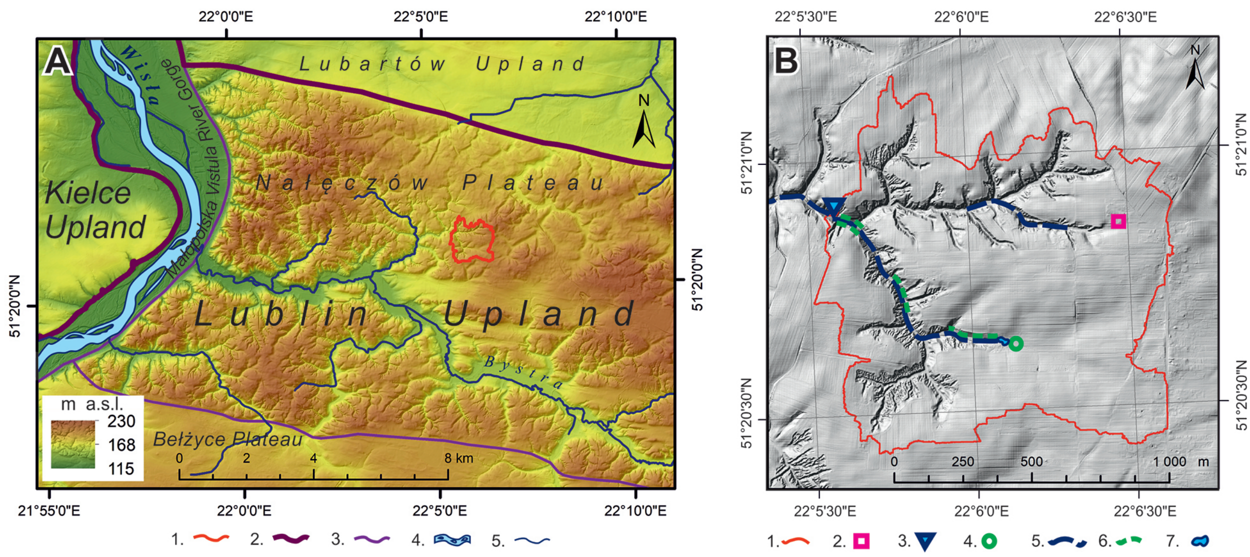

Fig. 1. A – Localisation of the study area on the DEM background: 1 – Kolonia Celejów catchment, 2 – macroregions border, 3 – mesoregions border, 4 – the Vistula channel, 5 – stream channel; B – Relief and hydrological conditions of the studied catchment in Kolonia Celejów (Hillshade Relief Model – DEM: https://mapy.geoportal.gov.pl): 1 – catchment border, 2 – rainfall station, 3 – hydrological station, 4 – spring, 5 – periodical stream, 6 – seeps and exudates, 7 – pond.

two main gully forms, each about 1 km long, merge into a 200-meter-long common mouth section (Fig. 1B). They are reached by side arms 100–300 m long and numerous side landforms up to 50 m long, often dead-end or overhanging, forming characteristic badlands-relief. In total, the density of the gully network in the catchment area of 1.24 km^2, exceeds 6 km · km^{-2} (Rodzik, Zgłobicki 2000, Rodzik et al. 2009). Despite the significant dissection by a gully network, the catchment has preserved several natural drainless depressions of complex origin (Maruszczak 1958, Kołodyńska-Gawrysiak, Chabudziński 2012, 2014). In addition, the trough-shaped bottom of the main valley in the upper section not dissected by the gully is baffled by an elongated cone at the outlet of a small sunken lanes (Rodzik et al. 2014). These concave formations trap runoff thus reducing the actual drainage area to about 1 km^2 (Fig. 1B).

At sites in the gully bottom of poorly permeable clays and weathered siwak, seeps and exudates occur at several levels (185–165 m a.s.l.), feeding short, intermittent streams (Fig. 2). The largest of these, with a flow rate of about 1 dm^3 · s^{-1}, discharged from a source at the head of the main gully dissecting the bottom of the dry valley and, after flowing 200–500 m, usually disappeared into the sands at the bottom of the gully in dry years, whereas in wet years it flowed through the entire gully. Currently, the source directly feeds a 5–6 m deep pond, reactivated in 2015, while the outflowing watercourse functions in wet years, allowing calibration of the water level recorder.

The study area is characterised by a moderate, transitional climate with continental and oceanic influences. The average annual air temperature is 7.7°C, July temperature is 18.1°C and January temperature is −3.4°C (2008). The average annual precipitation total sum here reaches about 600 mm and is 50 mm higher than in neighbouring regions (Siwek 2006). Higher, by 10–20 mm, is thus the average annual runoff, 120 mm, of which 90 mm, is subsurface runoff (Michalczyk, Wilgat 1998). Precipitation of the summer half-year prevails (380 mm) and the highest average monthly rainfall, 83 mm, falls in July. Once every few years rainfall with a daily total of about 50 mm is recorded and every few decades catastrophic rainfall occurs, with a daily total approaching 100 mm (Rodzik et al. 2021). Snow cover remains in this area for 75–80 days,

Fig. 2. Measurement of snowmelt flow at the hydrometric cross-section closing the gully catchment (photo by J. Rodzik).

triggering moderate snowmelt runoff (<20 mm) every few years. Though recorded in the second half of the 20th century, extreme snowmelt, even >50 mm, does not occur nowadays (Mazur, Pałys 1992, Gardziel, Rodzik 2005, Rodzik et al. 2009, Janicki et al. 2010).

The diversity of environmental conditions results in numerous, physiographic boundaries and a landscapes mosaic, since 1979 legally protected as the Kazimierz Landscape Park. Despite this, the region has been in long-term and intensive agricultural use. Approximately 70% of the study catchment area consists of agricultural land, with an equal share of arable fields and berry bush plantations. Traditional, family run, smallholder (<10 ha) farms with highly fragmented arable fields still dominate here (Rodzik, Zgłobicki 2000). In the gullies, there has been a secondary succession of forest with the participation of hornbeam, linden, oak, maple, ash, elm and in places pine, which are restoring the communities of oak-hornbeam forest (*Tilio-Carpinetum*). Despite the afforestation, the bottoms and edges of the main and side arm gullies are dissected during downpours and snowmelt (Rodzik, Zgłobicki 2000, Rodzik et al. 2009, Kociuba et al. 2014, 2015).

Materials and methods

Precipitation and runoff measurement

Atmospheric precipitation was recorded using a heated TPG-023 digital pluviograph from

A-STER, with a precipitation step of 0.1 mm (resolution) and a time step of 1 s. Such recording made it possible to determine the instantaneous rainfall intensity, important for statistical calculations of rainfall-runoff relationships. Measured data for calculating water runoff was obtained from a hydrological station installed at the mouth of the gully, consisting of a Thomson triangular weir, a water gauge patch and a digital recorder 'Thalimedes' developed by OTT company (Fig. 2).

Recording of data done in HYDRAS software (OTT HydroMet), occurred every 10 min with an accuracy of 1 mm. The water flow is calculated from the water levels according the Thomson's formula (Byczkowski 1999):

$$Q = 1.4h^{5/2} \quad (1)$$

where:
- Q – water flow [m^3/s],
- h – water levels [m].

Due to the number of data, they were usually compiled on a monthly basis, according to hydrological years, covering consecutive months from November to October of the following calendar year. The warm half of the year covers the period from May to October (V–X) and the cold half-year from November to April (XI–IV). Effective precipitation includes all precipitation events which triggered water runoff from gully catchment. As a rule, water runoff was recorded with rainfall above 20 mm and sometimes above 10 mm, therefore these rainfall thresholds were used to distinguish days with precipitation.

Maximal rain intensity is obtained directly from the pluviography and rain efficiency is calculated as quotient of rainfall sum and rain maximal intensity. Runoff surface index and runoff coefficient calculated from the relationship of total runoff to catchment area and total rainfall.

Statistical analysis. The linear and non-linear modelling

The basic statistical analyses were performed in MS Excel. It was also used to fit linear models (rectilinear and curvilinear) to the distributions of the analysed parameters: rainfall and water runoff, and to determine the determination coefficient (R^2), allowing to estimate the quality of the model. On the contrary, the Statistica program (TIBCO Software Inc.) was used to perform linear correlation analysis, Statistica program adjust the linear regression models and their quality parameters and generate non-linear models using the segment regression equation:

$$y_1 = a_1x + K\ (x <= b) \text{ and } y_2 = a_2x + K\ (x > b) \quad (2),$$

where:
- a_1, a_2 – regression coefficients,
- K – free expression,
- x – independent variable, and
- b – breakpoint.

In the segmented regression analysis, the quasi-Newton estimation method and the number of iterations = 50 were applied. The breakpoint (b) was determined automatically and according to the user, so that the explanation of the variance of the variable was the largest. A standard level of statistical significance was also adopted for the generated models, i.e. $a = 0.05$. Due to the amount of data, regression analysis was performed for water runoff on an annual, seasonal and monthly basis.

Results

Temporal rainfall distribution

The several-year period preceding the 20-year registration series was characterised by high annual precipitation totals and extreme events, such as intense snowmelt in the spring of 1996 and two heavy rainstorms, in September 1997 and June 1999. Numerous active erosion and piping landforms remained, including the dissection of the bottom of the gully (Rodzik, Zgłobicki 2000, Zgłobicki 2002). Weather conditions varied throughout the study period. There were large fluctuations and contrasts in the annual and seasonal distribution of precipitation. These are distinctive features of the 'capricious' climate of the Lublin Upland (Siwek 2006, Kaszewski 2008, Janicki et al. 2014, Janicki 2016).

In terms of annual precipitation total sums, according to Kaczorowska's (1962) classification, normal years (90–110% of the average) prevailed in the study catchment between 2003 and 2022. Precipitation total sums, close to the average, occurred in as many as 12 cases, while 4 years were classified as wet (111–125% of average), 2 as extremely dry (below 50% of average), and 1 each as dry (75–89% of average) and extremely wet (above 150% of average). There were no years classified as very dry (50–74% of average) and very wet (126–150% of average). In recent years, the spread of precipitation sums has increased, as evidenced by the occurrence of both extremes of annual precipitation total sums in the last 3 years of the 20-year measurements period (Fig. 3).

Precipitation of the warm half-year, from May to October, was predominant (average 382 mm), with totals ranging from 175 mm to 535 mm (Fig. 4). The precipitation of the cold half-year (from November to April) reached values from

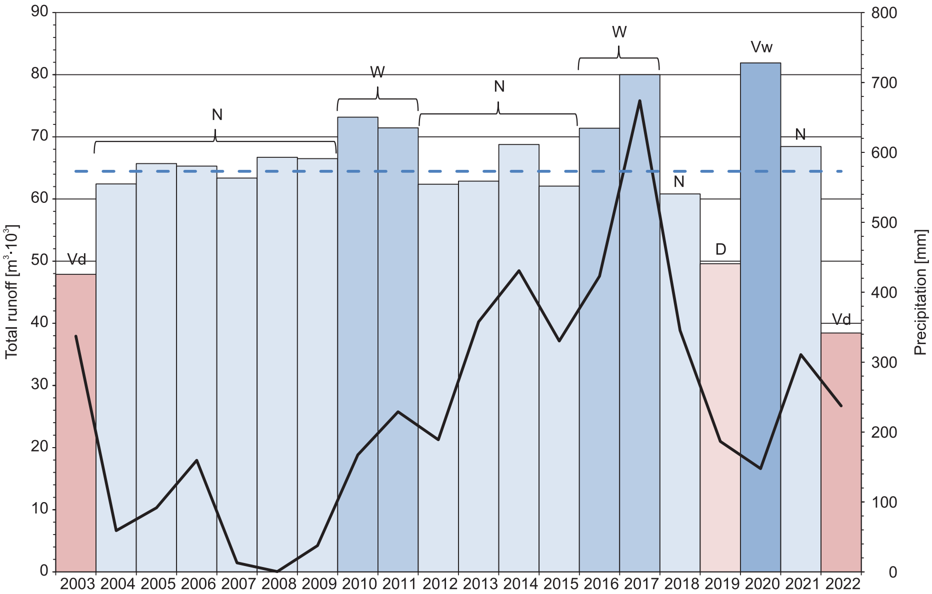

Fig. 3. Distribution of annual sums of precipitation and annual volumes of water runoff from the gully catchment for the years 2003–2022; precipitation classification according to Kaczorowska (1962): Vd – extremely dry year, D – dry year, N – average, W – wet, Vw – extremely wet and blue dotted line means the average precipitation for total period.

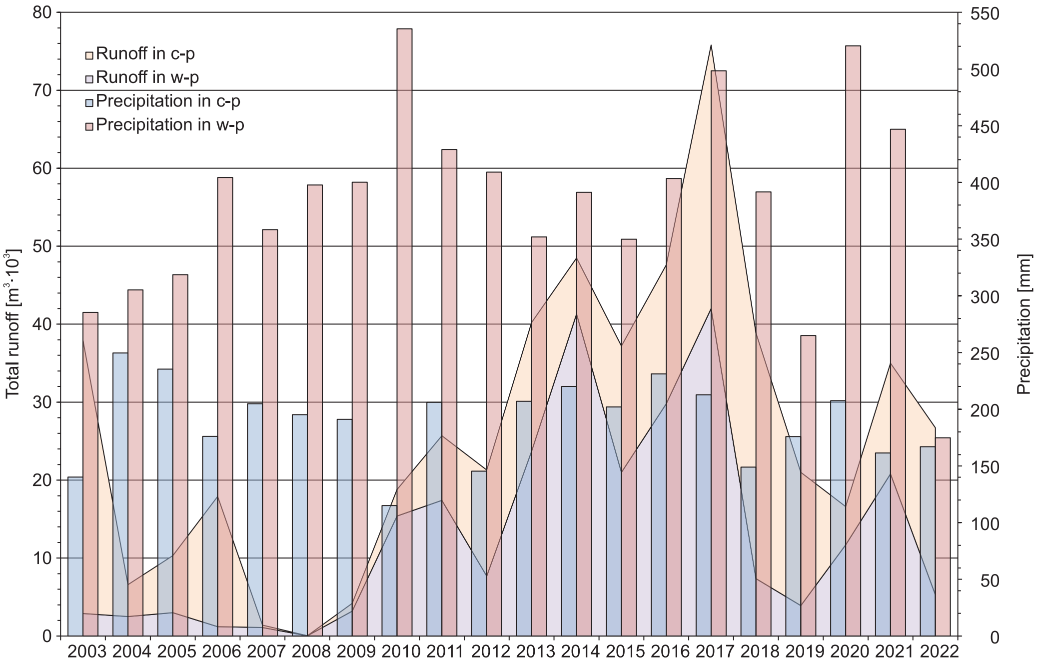

Fig. 4. Distribution of half-year precipitation and water runoff from studied gully catchment in Kolonia Celejów in 2003–2022; c-p – cold half-year, w-p – warm half-year.

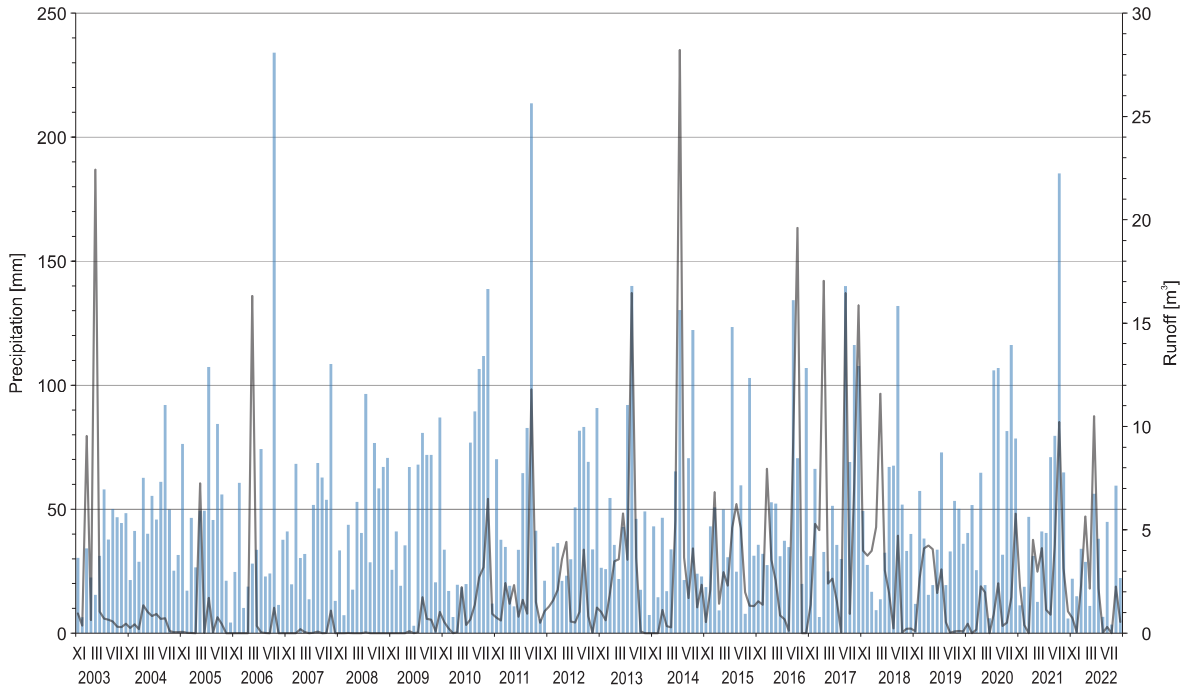

Fig. 5. Monthly precipitation total sum and runoff between 2003 and 2022 in the studied gully catchment.

115 mm to 250 mm (average 190 mm). Monthly precipitation maxima occurred only in the warm half-year and the month with the highest precipitation most often was July (average 82 mm) with a maximum of 213.6 mm in 2011.

In August 2006, precipitation total sums were as high as 234 mm, a record for the entire 20-year series of surveys. Probably this is an absolute record, as this month saw a then-record monthly precipitation sum at many meteorological stations in the Lublin region. In the study catchment, the sum of monthly precipitation repeatedly exceeded 100 mm such as 138.8 mm in September 2010, 140.1 mm in June 2013, 130.2 mm in May 2014 or 116.2 mm in October 2020 (Fig. 5). Such a spread of maximum precipitation total sums characterises the transient nature of the Lublin Upland climate (Siwek 2006, Kaszewski 2008, Janicki et al. 2011). The lowest monthly precipitation total sums were recorded mostly in February (mean 29 mm) and sometimes also in November, October or January.

Effective rainfalls

Effective daily precipitation, resulting in surface runoff, began with totals of 7–10 mm, depending on temporary environmental conditions (Table 1).

Daily precipitation >10 mm occurred from 6 to 25 times a year, with an average of 15 cases (Table 1), typical of the Lublin region (Kaszewski 2008). Precipitation >20 mm per day and intensity >0.5 mm per min in the nature of torrential downpours was recorded several times a year (an average of 4 per year). During the 20-year study period, there were no extreme heavy precipitation events with high totals and high intensity at the same time. Also, long periods (seasons) of precipitation, with above-average rainfall totals, shaping the dynamics of runoff were not observed. Meanwhile, the occurrence of several precipitation events in direct succession was recorded, while between 2003 and 2006, thaws and melts were superimposed with rainfall, accelerating the thawing of snow (Table 2).

In this context, the greatest hydrological impact was caused by frontal torrential rainfall, which occurred in 2010, 2014, 2016 and 2021. The largest temporary water runoff was generated by single rainfall events with a yield of >30 mm (Table 2).

Temporal structure and dynamics of water runoff

In the first half of the monitored 20-year period, annual values of water runoff ranged from

Table 1. Hydrological results of mostly effective rainfalls in the Kolonia Celejów in 2003–2022.

Date of rainfall	Coefficient								Remarks
	Rainfall sum [mm]	Max rain intensity [mm·min.$^{-1}$]	Rain efficiency[3]	Max discharge [dm·s^{-1}]	Total surface runoff [m^3]	Runoff surface index [mm]	Runoff coefficient [%]	Max spec. runoff [dm^3·s^{-1}·km^{-2}]	
4.V.2005	64.5	0.6	38.7	167.8	1620.0	1.3	2.0	135.5	downpour
31.VII.2005	34.3	2.4	82.3	283.6	932.7	0.8	2.2	228.7	downpour
4.VIII.2005	17.8	0.9	16.0	59.1	181.2	0.1	0.8	47.7	downpour
18.VIII.2006	14.9	2.9	43.2	57.0	205.3	0.2	1.1	41.2	downpour
20.VIII.2006	28.0	2.4	67.2	193.4	766.7	0.6	2.2	156.0	downpour
10.06.2009	24.3	1.1	26.7	146.1	433.5	0.3	1.4	117.8	downpour, damp ground,
23.VIII.2009	33.9	0.5	17.0	65.1	500.9	0.4	1.2	52.5	continuous rain, dry ground
14.VI.2010	30.1	1.5	45.2	273.0	704.6	0.6	1.9	220.2	continuous rain, damp ground
18.VII.2010	38.4	1.9	73.0	473.6	1784.0	1.4	3.7	381.9	downpour, dry ground,
6.VIII.2010	24.7	1.4	34.6	273.0	624.9	0.5	2.0	220.2	continuous rain, damp ground
31.VIII–2.IX.2010	100.2	0.6	60.1	81.3	7084.6	5.7	5.7	65.6	continuous rain, damp ground
6.VII.2011	24.3	0.8	19.4	300.0	2253.6	1.8	7.5	241.9	continuous rain, damp ground
18.VII.2011	18.2	1.4	25.5	163.8	665.6	0.5	2.9	132.1	continuous rain, damp ground
20.VII.2011	27.2	1.5	40.8	372.7	2198.4	1.8	6.5	300.6	continuous rain, damp ground
1.VII.2012	20.8	1.3	27.0	273.0	624.9	0.5	2.4	220.2	continuous rain, dry ground,
4.VII.2012	25.2	1.9	47.9	423.7	922.6	0.7	3.0	341.7	continuous rain, damp ground
11.VI.2013	38.4	1.4	53.8	714.8	5253.8	4.2	11.0	576.5	continuous rain, damp ground
23.VI.2013	19.0	1.6	30.4	863.2	5641.1	4.5	23.9	696.1	downpur, damp ground
27.04.2014	14.5	1.5	21.8	84.3	4286.5	3.5	23.8	68.0	continuous rain, wet ground
15–16.05.14	29.3	0.3	8.8	201.1	9931.3	8.0	27.3	162.2	continuous rain, damp ground
16–18.05.14	36.6	0.5	18.3	247.5	10508.2	8.5	23.2	199.6	continuous rain, wet ground
29.05.2014	11.7	0.4	4.7	62.3	2028.1	1.6	14.0	50.2	continuous rain, dump ground
7.08.2014	18.3[1]	4.8[2]	88.3	108.9	909.5	0.7	4.0	87.8	continuous rain, dump ground
26–27.05.2015	34.1	0.4	13.6	38.7	1416.1	1.1	3.3	31.2	continuous rain, wet ground
27.07.2016	11.9	1.3	15.5	171.0	730.2	0.6	4.9	137.9	downpur, dry ground
29.07.2016	31.4	1.6	50.2	232.9	1574.9	1.3	4.0	187.8	downpur, wet ground
31.07.2016	7.8	0.8	6.2	338.9	1098.1	0.9	11.4	273.3	downpur, wet ground
9–11.08.2016	46.7	1.3	60.7	828.1	10320.3	8.3	17.8	667.8	continuous rain, dry ground
19–20.07.2017	64.7	1.6	103.5	665.5	6540.0	5.3	8.2	536.7	continuous rain, dry ground
20.07.20l7	18.6	1.4	26.0	752.1	2370.0	1.9	10.3	606.5	downpur, wet ground
19–20.08.2017	34.8	0.7	24.4	37.9	605.3	0.5	1.4	30.6	downpur, damp ground
29.10.2017	24.3	0.8	19.4	81.1	1272.8	1.0	4.2	65.4	continuous rain, damp ground
16.07.2018	29.5	0.9	26.6	110.4	1213.8	1.0	3.3	89.0	continuous rain, damp ground
19.07.2018	30.8	1.9	58.5	358.7	2360.5	1.9	6.2	289.3	downpur, damp ground
27.05.2019	14.4	1.6	23.0	112.7	857.8	0.7	4.8	90.9	continuous rain, damp ground
29.06.2020	12.8	0.6	7.7	132.1	711.0	0.6	4.5	106.5	downpur, wet ground
26–27.09.2020	49.0	0.3	14.7	14.1	831.1	0.7	1.4	11.4	continuous rain, damp ground
13.10.2020	18.7	0.3	5.6	30.4	907.1	0.7	3.9	24.5	continuous rain, wet ground
29.07.2021	15.1	0.8	12.1	209.8	2518.7	2.0	13.5	169.2	downpur, damp ground
23–24.08.2021	84.3[1]	0.8	67.4	95.5	7348.7	5.9	7.0	77.0	continuous rain, damp ground
11.09.2022	16.9	0.1	1.7	27.6	1913.8	1.5	9.1	22.3	continuous rain, wet ground

[1)] in Rogalów rain station.
[2)] per hour.
[3)] sum x maximal intensity.

Table 2. Monthly sums of total surface runoff (m^3) in the Kolonia Celejów catchment in 2003–2022.

Year	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX	X	Cool half-year	Warm half-year	Annual runoff	Runoff days	
																all	> 40 m^3
2003	954	370	9537	637	22422	1040	700	653	564	307	293	455	34960	2972	37932	–	–
2004	257	430	194	1343	1030	830	926	689	722	107	45	51	4084	2540	6624	–	–
2005	64	14	5	0	7246	7	1705	38	774	450	3	0	7336	2970	10306	–	–
2006	0	0	0	0	16320	347	35	10	1	1230	0	0	16667	1276	17943	–	–
2007	0	0	0	191	56	0	17	74	1	8	1097	0	246	1197	1443	23	4
2008	0	0	5	0	0	0	38	0	0	0	0	0	5	38	43	5	0
2009	0	0	0	0	95	0	34	1742	693	655	86	1025	95	4236	4330	74	22
2010	540	234	0	39	2228	400	666	1390	2697	3180	6500	942	3442	15374	18816	303	83
2011	739	615	2418	1425	2326	805	1616	943	11798	1516	510	1064	8328	17446	25774	356	130
2012	1286	1602	2104	3585	4417	566	519	1040	4049	827	20	1236	13561	7691	21252	204	118
2013	1030	628	1987	3479	3572	5794	3554	16455	3649	84	0	0	16490	23742	40232	278	166
2014	0	0	1122	342	285	5457	28216	3659	1696	4106	1248	2345	7205	41270	48475	300	100
2015	541	2112	6820	1426	2947	2306	5088	6244	5048	1985	1332	1304	16152	21001	37152	358	208
2016	1546	1379	7954	3546	2550	857	677	114	9350	19612	0	0	17832	29753	47585	272	127
2017	1380	5291	4983	17055	2408	2640	1531	58	16448	933	7237	15859	33756	42066	75822	280	217
2018	3994	3750	3985	5132	11589	3041	1943	231	4717	44	215	225	31492	7375	38866	267	205
2019	94	2638	4099	4238	4063	1946	3091	534	19	91	108	83	17078	3926	21004	222	150
2020	458	0	179	2265	1974	0	936	2417	354	507	1742	5781	4876	11736	16612	206	116
2021	2205	394	0	4514	2980	4118	1128	899	4306	10215	3135	1059	14210	20741	34951	246	174
2022	729	58	2322	5647	2155	10496	2169	27	304	0	2255	550	21406	5305	26711	237	139
2003–2022	791	976	2386	2743	4533	2032	2729	1861	3360	2293	1291	1599	13461	13133	26594	227*	122*

* in hydrological years 2007–2022.

43 m^3 in 2008 to almost 40,000 m^3 in 2003 (Table 3). The extremely dry year of 2003 maintained the base runoff of water stored in the loess cover in previous years (Fig. 6). In 2003–2006, cold half-year runoff (4000–35,000 m^3, with an average of 9200 m^3), associated with snowmelt, predominated. The highest snowmelt runoff usually occurred in March (Fig. 6).

In 2003, mid-winter January melt (in the middle and end of the month) was also productive, with an effect enhanced by rainfall. Warm-season half-year runoff totals in those years (1300–3000 m^3) were only comparable to some monthly totals: in May 2005 (1700 m^3) and August 2006 (1200 m^3). In the following years, 2007–2009, runoff was extremely low, with no runoff at all in many months (Fig. 6), while in 2008 it occurred only in January and May. After this calm period, there was a surge in the volume of water runoff in the following years, boosted in part by the stabilisation of the baseline runoff. The average annual water runoff in 2010–2018 was 40,000 m^3, and in 2017 a maximum runoff about 76,000 m^3 was recorded. The relatively long, wet period was predominated by warm half-year outflows, ranging from about 7400 m^3 to about 4200 m^3

Table 3. Annual outflow rates from the gully catchment

Year	Precipitation total sum	Runoff	Runoff surface index	Runoff coefficient
	[mm]	[m^3]	[mm]	[%]
2003	426	37932	30.6	7.2
2004	555	6624	5.3	1.0
2005	554	10306	8.3	1.5
2006	580	17943	14.5	2.5
2007	563	1443	1.2	0.2
2008	593	43	0.0	0.0
2009	591	4330	3.5	0.6
2010	650	18816	15.2	2.3
2011	635	25774	20.8	3.3
2012	555	21252	17.1	3.1
2013	559	40232	32.4	5.8
2014	611	48475	39.1	6.4
2015	552	37152	30.0	5.4
2016	635	47585	38.4	6.0
2017	711	75822	61.1	8.6
2018	541	38866	31.3	5.8
2019	441	21004	16.9	3.8
2020	728	16612	13.4	1.8
2021	608	34951	28.2	4.6
2022	342	26711	21.5	6.3
2003–2022	572	26594	21.4	3.7

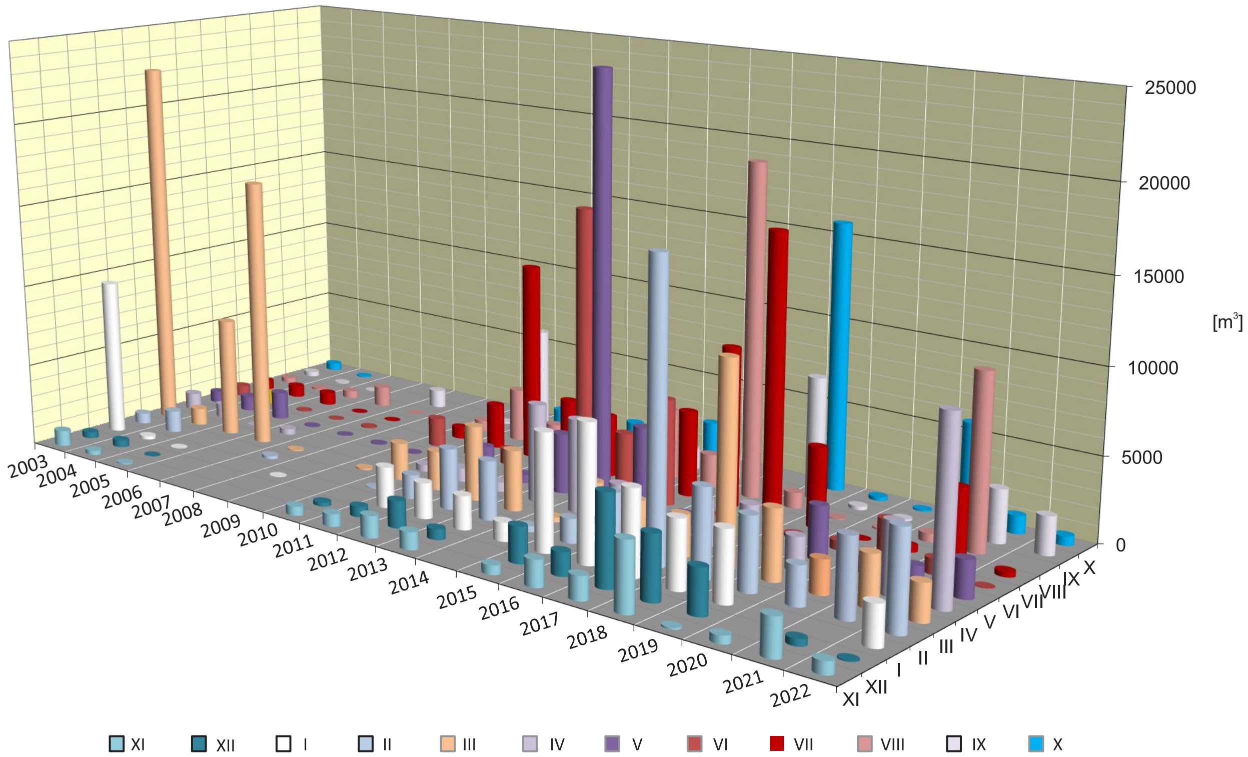

Fig. 6. Monthly water runoff sums distribution from the loess gully catchment Kolonia Celejów in the 20-year period 2003–2022.

(average about 2300 m^3), mainly in May (2014), July (2011, 2017) and August (2017). In the cold half-year, the highest runoffs were recorded in January and February (2014), despite the periodic disappearance due to freezing of the base runoff stream. In the last 20-year measurement period of 2019–2022, the average annual water runoff slightly decreased to a value close to the average for the entire measurement period (almost 2500 m^3). However, its fluctuations in different scales: annual, seasonal and monthly increased significantly (Fig. 6A) The highest runoff in this period occurred in 2021 and amounted to about 35,000 m^3 (Table 2). The runoffs of the warm and cold half-years were similar, ranging from about 5000 m^3 to 21,400 m^3 with an average of 14,400 m^3. Cold half-year runoffs were relatively even, with predominating snowmelt runoffs in February and March. Warm half-year runoffs reached similar values, but their monthly magnitudes varied more (Fig. 6B). Runoffs predominated in August (2021), October (2020) or May 2019 and 2022 even in September.

Runoff periodicity

Periodicity in water runoff from the catchment, which occurred throughout the 2003–2022 measurement period, became apparent in the form of four periods with different precipitation regimes and consequently, with different volumes and patterns of water runoff (Figs 7A–C). The 2003–2006 period was dominated by runoffs of the cold half-year (4–35,000 m^3, with an average of 9200 m^3), associated with snowmelt.

The highest snowmelt runoff usually occurred in March (Fig. 7B). In 2003, mid-winter January snowmelt (in the middle and end of the month) was also productive, with the effect enhanced by rainfall. In 2010–2018, annual precipitation total sums were high, ranging from 541 mm to 711 mm (Table 4). The number of days with precipitation >10 mm was highly variable (from 6 to 25), but daily total sums did not exceed 41 mm. Against this background, the very wet year 2010 stood out, with abundant precipitation and high annual total sums. In general, an upward trend in water runoff from the catchment prevailed (Fig. 7C). Winters were not very snowy; an average of 64 days with snow cover occurred. The lack of snowmelt runoff was compensated by numerous summer rainstorms, generating rapid surface runoff (Kociuba et al. 2014, 2015), conditioned by earlier ground saturation. Such a relationship is well illustrated by the case of the precipitation/runoff relationship in May/June 2013 (Fig. 7B). In the following years, 2019–2022, annual precipitation total sums were the most variable, ranging from 342 mm to 728 mm, making the averaged precipitation conditions close to the multi-year average (Table 4). The exceptional year in this regard was 2020, with a maximum number of days with rainfall of >10 mm and a maximum annual rainfall total of 728 mm. Winters were generally low in snow, with cover lingering from 5 days to 59 days. Despite this, the proportion of pronivial to propluvial runoff was equalised in the annual water runoff (Table 4). The year 2022 was exceptionally dry, and despite the occurrence of snowmelt, a decrease in water runoff was observed.

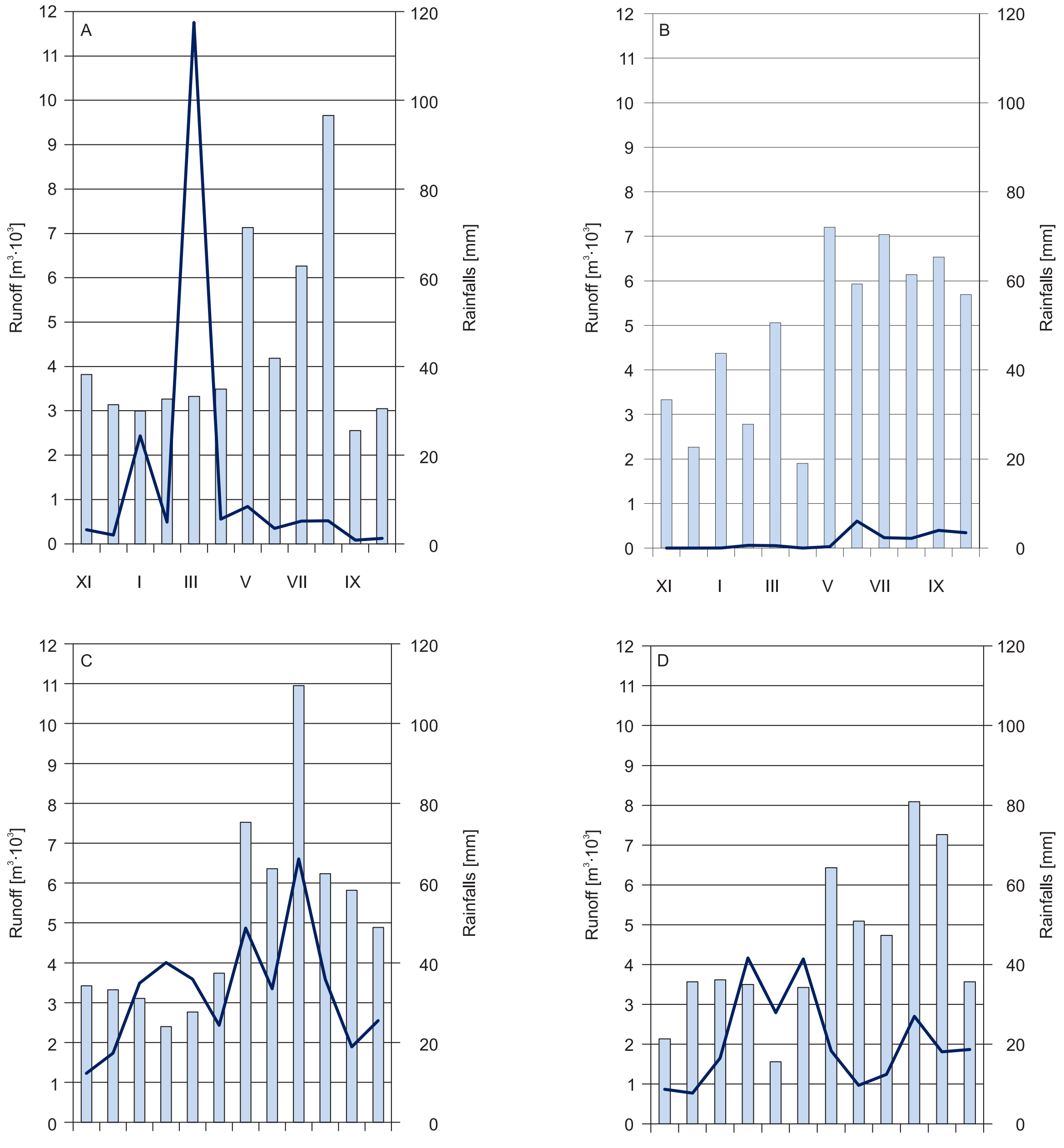

Fig. 7. Average monthly precipitation total sums and runoff in the gully catchment: A – nival period 2003–2006, B – steady period 2007–2009, C – pluvial period 2010–2018, D – variable period 2019–2022.

Table 4. Periodicity of water runoff from the Kolonia Celejów gully for the years 2003–2022.

Type of period	Unit	Nival			Steady			Pluvial			Variable			Total series
Years (XI–X)		2003-2006			2007-2009			2010-2018			2019-2022			2003–2022
Data type		Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Mean
Precipitation sum year	[mm]	426	584	536	563	593	582	541	711	605	342	728	504	572
Days >10 mm	[–]	10	20	14	13	15	14	11	21	14	6	25	14	15
Precipitation max daily	[mm]	19.0	64.5	35.6	25.4	32.5	28.9	23.6	61.0	37.3	17.5	40.8	26.5	33.5
Snow max thickness*	[mm]	320	440	355	140	260	210	110	460	228	30	260	178	241
Days with snow cover*	[–]	84	159	113	34	80	58	27	118	64	5	59	39	68
Outflow total	[x10^3 m^3]	6.6	37.9	18.2	0.04	4.2	1.9	18.8	75.8	39.3	16.6	35.0	24.8	26.6
a) cold half-year (XI–IV)		4.1	35.0	15.8	0.01	1.0	0.4	3.4	33.8	16.5	4.9	21.4	14.4	13.5
b) warm half-year (V–X)		1.24	3.0	2.4	0.03	3.2	1.5	7.4	42.0	22.9	3.9	20.8	10.4	13.1

* Data form the Lublin-Radawiec IMGW Station.

Discussion

Runoff regime and rainfall-runoff relation modelling

Water runoff for averaged months of the entire 20-year measurement period does not differ significantly from the hydrogram for rivers of the Lublin Upland, with a complex ground-snow-rain regime (Michalczyk, Wilgat 1998, Kociuba, Stępniewska 2002). The annual course distinguishes a snowmelt maximum and a secondary bipartite precipitation maximum, with climaxes in July and May. The low-flow period lasts from September to December, with a slight increase in October. This pattern of annual gully runoff shows increasing instability. This may be a response to changes in the distribution of major atmospheric circulation types observed in this part of Europe (Wibig 2001, Lorenc et al. 2012, Araźny et al. 2021). The tendency, characteristic of the second half of the 20th century, to lengthen the periods between productive melts continues (Rodzik et al. 2021). Similar trends for snowmelt

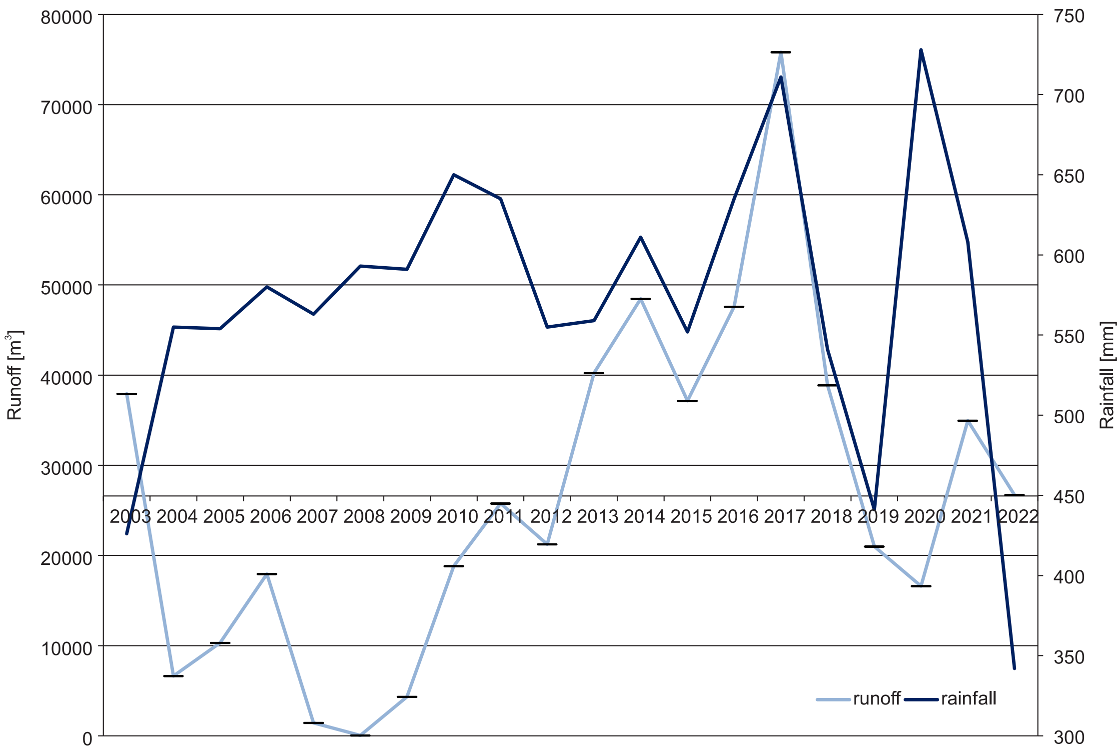

Fig. 8. Multi-year distribution of the precipitation total sums and annual runoff between 2003 and 2022 from the gully catchment. Position of X axis determines the average annual water runoff from the catchment.

in the Central Volga region (Russia) are documented by Yermolaev et al. (2022). However, the lack of a consistent trend in the amount of annual water runoff is confirmed, as it was for annual precipitation totals in Central Europe during the 20th century (Niedźwiedź et al. 2009).

An increase in annual precipitation total sums (Fig. 8), especially summer precipitation, is mainly responsible for the increase in water runoff from the gully during the pluvial period.

A decrease in annual precipitation total sums and summer precipitation in 2012, 2013 and 2015, as well as a decrease in winter precipitation in 2012 and 2015 determined the trend reversal. At the same time, there were numerous rainstorms, especially in 2015 and 2017, which determined the maximum seasonal and annual runoffs. The overall decreasing trend of annual water runoff in the recent period is interrupted by the outstandingly wet year of 2020, with peak annual precipitation and high warm half-year precipitation (Fig. 8). The continuation of the increase in runoff in the following year, is the result of high summer precipitation total sums and the occurrence of downpours (Table 1). The years 2019 and 2021 are also marked by an increase in winter precipitation (Fig. 5). The exception, however, becomes the extremely dry hydrological year of 2022, but with a runoff close to the multi-year average. The precipitation of 2020 and 2021 renewed the water resources of the catchment so that a relatively high baseflow was recorded. A 2-year delay in the response to precipitation in the Lublin region was noted when analysing groundwater table fluctuations and the occurrence of low-flow period in river (Janicki et al. 2011).

Linear correlation between precipitation total sums and runoff from the gully catchment, calculated for annual, seasonal, monthly actual and averaged data, showed no statistically significant relationship between the variables ($r < 0.5$). Also, linear regression analyses showed no statistically significant relationships. As shown, in the case of the occurrence of a series of high precipitation after a dry period and a wet period (Fig. 5), runoff is determined by the instantaneous retention capacity of the catchment. Thus, the direct effect of precipitation pattern on runoff dynamics seems clear for the 2010–2018 pluvial period, for monthly precipitation of the warm half-year.

Therefore, a non-linear regression analysis was performed for the same data (Table 5). The results of the segmented regression method used showed significant ($R^2 > 0.5$) and strong relationships ($R^2 > 0.7$) between precipitation total sums and gully water runoff. The best model fit was obtained for the hydrological year and the warm half-year (Table 5). Weaker model fit and lower coefficient of determination were found for the cold half-year and monthly data. These relationships are complex and difficult to fit into a mathematical model. An attempt to determine precipitation/runoff relationships for three gully catchments on the Nałęczów Plateau was made by Józefaciuk and Karczewski (1991), by using data from water gauge readings daily. They explained the radically different results obtained from neighbouring catchments by the variation in such parameters as the degree of afforestation of steep slopes, soil erosivity, distribution of fields and thickness of loess cover, while they did not take into account the different shape and elongation of catchments.

The role of retention in runoff

The maximum daily water runoffs from the gully were generated by intense snowmelt and

Table 5. Segmental regression models of the rainfall/gully water runoff relationship.

Data	Equation	Determination coefficient (R^2)	Break point (b)
Monthly	$y = 68x + 487$ and $y = 18.4x + 5235$	0.62	2216.0
Half year: XI–IV	$y = 26.3x - 1377$ and $y = -47.8x + 29783$	0.63	13461.0
Half year: V–X	$y = 11.5x - 853$ and $y = -6.9x + 29353$	0.73	196.8
Hydrological year	$y = 9.4x + 7610$ and $y = 96.6x - 10434$	0.79	26593.0
Average monthly: 2003–2022	$y = 16x + 747$ and $y = -8.6x + 3464$	0.64	2216.0
2003–2006	$y = 6x + 98.6$ and $y = 2782x - 80825$	0.99	1517.0
2007–2009	$y = 0.5x + 3.4$ and $y = -12x + 1153$	0.90	161.6
2010–2018	$y = 18.3x + 1193$ and $y = 29.7x + 2534$	0.82	3277.6
2019–2022	$y = 2.8x + 1216$ and $y = -24.3x + 4372$	0.80	2068.4

rainstorms, especially torrential rainfall (Table 1). The total water runoff reached a maximum of 10,000 m^3, while the flow rate was more than 800 $dm^3 \cdot s^{-1}$. The specific runoff rate reached 700 $dm^3 \cdot s^{-1} \cdot km^{-2}$ and was similar to the rates of the river drainage catchments of low hydrological rank in the Lublin Upland (Maruszczak et al. 1984, Janicki et al. 2014, Janicki 2016). In the case of torrential rainfall, the high runoff rates were determined by the earlier saturation of the ground by the preceding rainfall (Figs 9A, B).

However, in no case did the unit surface runoff index rates exceed 9 mm, indicating that local retention: interception, detention and infiltration absorb most of the water in the water balance of the catchment. The variability of local conditions affects the variation of the runoff coefficient (from about 1% to 28%, average >7%). This testifies to the high water capacity of loess and the considerable retention capacity of the catchment, with a system of gullies overgrown with oak-hornbeam forest. This is especially evident in the dry season, as infiltration rates of loess in the dry state are high (Demczuk et al. 2022).

The catchment's retentivity became apparent, especially during the record daily and monthly precipitation for the entire 20-year period, which occurred during the first years of measurements. Despite the low precipitation, the basal runoff of water from the loess cover functioned in 2003–2004. The highest daily precipitation (64.5 mm) was recorded on 4 May 2005, as an all-day precipitation with significant runoff (Table 1). In contrast, the record monthly precipitation (234 mm) was gauged in August 2006 and consisted of 4 precipitation events >20 mm, most of which were retentive, as the summer had been very dry earlier. Disproportionately little surface runoff occurred only in the second half of August (Fig. 9A).

The role of gully in the water balance

The role of gullies in the water balance for branching and forested gully systems in loess areas is ambiguous and depends on local conditions and precipitation patterns. It is fairly unanimously accepted in the literature that gullies are lines of periodic water runoff and drain headwater catchments (Poesen et al. 2003). Loess catchments over agricultural use with young gullies in the Moldavian Highlands (Jonita 2006) and in the Loess Plateau of China (Chen et al. 2024) reduce water storage and facilitate rapid runoff into river channels. Also, individual loess gullies in the Lublin Upland, especially those of road genesis, channel and accelerate surface runoff (Ziemnicki, Naklicki 1971, Józefaciuk, Karczewski 1991,

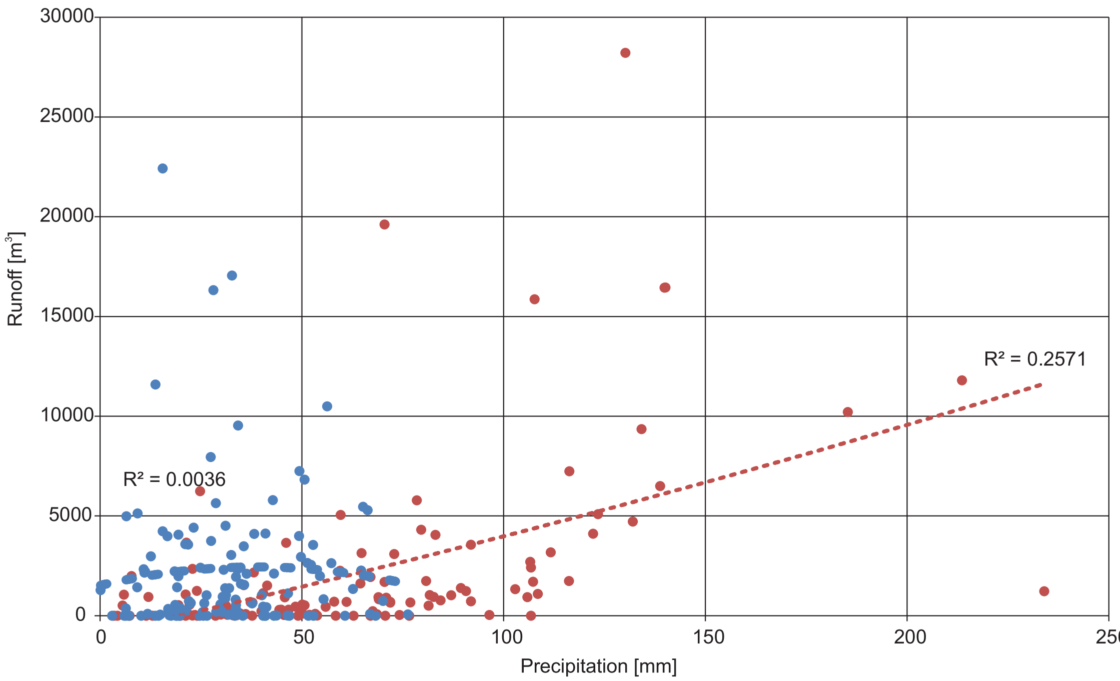

Fig. 9. Response of a loess gully catchment water runoff to a downpours series depending on the preceding conditions: A – during the dry period, B – during the wet period.

Mazur 2008). Froehlich (1982) attributed a similar role of gullies in the riparian zone of the Carpathian catchment. On the other hand, it seems that branching loess gullies with permanent vegetation cover inhibit surface runoff and increase the retention capacity of the catchment (Mazur, Pałys 1991) as is evident from observations on gully runoff on the Nałęczów Plateau, among others (Józefaciuk, Karczewski 1991.

The Kolonia Celejów gully system, with its large number of drainless, retains rainwater from low- and moderate-efficiency precipitation. Once the rainfall total exceeds about 10 mm, rapid surface runoff (quick flow) occurs when it overlaps with the base runoff. In the study catchment, the unit runoff coefficient is low, ranging from 1% in the stable period, 2–6% in the variable period up to about 8% of annual precipitation in the nival and pluvial periods, which confirms the significant role of the degree of water saturation of the loess cover in shaping runoff. The highest values were recorded in June 2013 as a result of the superimposition of two rainstorms (clustering) under conditions of high moisture content of the loess cover in the preceding period (Fig. 7B). Studies conducted in dry denudation valleys (Ziemnicki, Orlik 1971, Janicki 2014, 2016) have shown that natural relief adapted to episodic runoff drains more easily than in the case of gullies with an undeveloped channel and uneven bottom with absorbent litter. During the 2003–2022 measurement period, the annual runoff rate in the Kolonia Celejów gully catchment did not exceed 9% of annual precipitation (Table 3). In specific years, the runoff coefficient ranged from 0% to 8.6% (mean < 4%). The highest values of this coefficient were obtained for the wet year 2017 with numerous rainstorms and the dry year 2003, but with extreme snowmelt. On the other hand, in the extremely wet year 2020, the coefficient was quite low after a dry year, in the absence of torrential rainfall, suggesting a high absorptive capacity of the loess cover.

Conclusions

The small and compact loess gully catchment in the Kolonia Celejów, with episodic-periodic runoff, fulfils the conditions of a representative catchment for the loess areas with high gully density, with the possibility of giving a homogeneous measurement series despite high water runoff variability.

In the 20-year measurement series, four multi-year periods with similar in particular years hydro-meteorological indicators were distinguished: the nival period (2003–2006), with a predominance of snowmelt runoff; the stable period (2007–2009) without runoff; the pluvial period (2010–2018) with numerous rainstorms; and the variable period (2019–2022) with a changing dominant type.

Inter-annual and seasonal different weather conditions decided on the exceptional variability, irregularity and diversity of water runoff from the gully catchment in short and long time scales. The amount and dynamics of water runoff is linked to the occurrence of a series of torrential rainfall and thaws and melts were superimposed with rainfall (so-called clustering phenomenon).

The maximal values of water runoff also depend on the weather conditions in the preceding period, shaping the retention capacity of the gully catchment. The high catchments' retention with thicker loess cover, which results in small annual values of the annual runoff coefficient <8%, should also be emphasised.

The role of forested, permanent gully systems in the water balance of catchments is not ambiguous. The widely accepted acceleration of water runoff does not occur in the cold half-year without snow cover, but snow cover delays this runoff, as does vegetation in the warm half-year.

The proportion, which varies from period to period, of propluvial and pronivial runoff evens out over the multi-year period. In contrast, a marked decrease in the snowiness of winters and the absence of intense snowmelt may change these proportions in favour of downpours and propluvial runoff.

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Authors' contributions

Conceptualisation: GJ, JR; methodology: JR, KS; software: GJ; validation: GJ, JR; formal analysis: JR, WK; investigation: KS, JR; resources: KS, JR; data curation: KS, GJ; writing – original draft preparation: GJ; writing – review and editing: JR, WK; visualisation: WK; supervision: JR, WK. The authors declare no conflict of interest in this study. All authors have read and agreed to the published version of the manuscript.

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