Co-occurrence probability of water balance elements in a mountain catchment on the example of the upper Nysa Kłodzka River

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Abstract
Conditions of the formation of key elements of the water balance, such as precipitation and runoff, and relations between them in the mountain catchment area are very complicated, conditioned both by the climatic factor and the physiographic characteristics of the catchment area. The aim of the study is to determine relations between precipitation and runoff in the Kłodzka Valley (KV) located in mountain areas of south-western Poland. Analyzes were based on precipitation in KV and discharges of the Nysa Kłodzka River and its tributaries, recorded in hydrological years 1974–2013. The bivariate Archimedean copulas were used to describe the degree of synchronicity between these variables. The study area shows a considerable variability in the conditions of transformation of precipitation into runoff. It is conditioned both by the pluvial regime and the physical-geographical characteristics of the catchment area. As a result, sub-catchments with diversified hydrological activity and their role in the formation of water resources of the entire KV were identified. Among them, the Biała Łądecka River sub-catchment was found to be the most hydrologically active, and the sub-catchment of Bystrzyca Dusznicka River the most inert, despite e.g. quite similar synchronicity of precipitation compared to the average precipitation in KV. At the same time, the KV rivers are characterized by different types of runoff regime and characteristic of the water balance structure. The methodology presented can be useful in determining dependencies between selected elements of the water balance and evaluation of water resources availability in source areas of mountain rivers.

Keywords Precipitation · Runoff · Bivariate copula functions · Synchronicity · Rainfall-runoff modelling · Runoff coefficient

Introduction
Environmental systems are characteristically complex and heterogeneous. Their processes and properties are often difficult to quantify at small scales and difficult to extrapolate to larger scales (Kirchner 2016). This is particularly evident for mountain headwater catchments where interactions between geology, geomorphology, vegetation and harsh topography, coupled with climatic forcing (sometimes distinctly different along elevation gradients) and multiple water inputs beyond rainfall (e.g., meltwater from snowpack, glaciers and permafrost, subsurface water from springs, talus and tile) make the hydrological response highly complex to decipher (Zuecco et al. 2018). It is generally agreed that mountain regions are of significant hydrological importance (Viviroli and Weingartner 2004). One of the major problems in understanding the hydrological cycle in high mountainous regions with much snow is evaluating the spatial and temporal distribution of precipitation (Tani 1996; Erxleben et al. 2002; Chubb et al. 2016; Guo et al. 2020). Runoff generation in mountain catchments is one of the most complex hydrological processes. It is highly variable in space and time, depending on the combination of three main controlling factors: (1) climate, (2) soil and geology, and (3) vegetation. The different combinations of these three factors determine the
water balance of landscape units, including soil moisture dynamics, evapotranspiration and runoff generation (Becker 2005). Water balance is the most important integral physical-o-graphic characteristic of any territory—it determines its specific climate features, typical landscapes and opportunities for human land use (Shiklomanov 2001). Water balance generally describes tracking the balance between flowing input/output water of any hydrological system (Abdollahi et al. 2019). Water balance estimation is an important tool to assess the current status and trends in water resource availability in an area over a specific period of time (Stauffer 2013). Proper descriptions of water balance elements allow for drawing respective conclusions for scientific debates and economic activities (Osuch et al. 2009). Furthermore, water balance estimates strengthen water management decision-making, by assessing and improving the validity of visions, scenarios and strategies (Stauffer 2013).

The structure of the catchment water balance is shaped mainly by climatic conditions, in particular, the temporal distribution and volume of precipitation, and by the physical and morphometric conditions of the catchment, including land use, land cover, and especially vegetation. To measure this structure, the runoff coefficient is applied. It reflects the effects of catchment imperviousness, infiltration, storage, evaporation, natural retention, interception, etc., which all have an effect on the volume losses and time distribution of the discharge hydrograph in arriving at the peak runoff rate. The runoff coefficient also varies with storm duration, soil type, surface slope, groundwater level, and the extent to which development has extended impervious coverage.

Depending on the temporal and spatial scale of a given study, knowledge of the rainfall-runoff relationship allows obtaining different hydrological characteristics. In the micro scale, it is necessary to estimate the maximum flood wave, the volume and temporal distribution of rainwater runoff. Analysis of these parameters is fundamental in designing of the water management devices such as stormwater drainage systems and structural stormwater control. Information on the rate and volume of rainwater runoff is essential in designing of stormwater management systems that aim at reducing numerous adverse effects, including flooding, erosion and property damage. In turn, in long-term periods, it allows determining the conditions for the formation of water resources and the characteristics of the water balance in various hydrological territorial units, from the catchment-scale to the country-scale.

The purpose of this study was to identify conditions shaping the co-occurrence of precipitation and runoff, along with relations between them in the mountain catchment of the Nysa Kłodzka River in south-western Poland, and on that basis determine the spatial differentiation of the structure of water balance in its individual sub-catchments. The Nysa Kłodzka River is located in the Kłodzka Valley (hereinafter referred to as KV) in the Sudetes Mountains. While KV is the second richest in water resources of the regions of Poland, after the Carpathians (Bednorz et al. 2019), it is also particularly susceptible to catastrophic floods triggered by excessive rainfall in summer, enhanced by morphological conditions of KV (altitude, exposure, terrain, etc.). To date, a number of studies have been carried out with regard to excessive precipitation and runoff, and relationships between them in that area (Wrona 2008; Łach 2009, 2012; Rutkowska et al. 2016; Niedzielski and Mizioński 2017; Jeziorska and Niedzielski 2018; Stodolak et al. 2018). Consequently, dependencies between extreme hydro-meteorological events in KV have been relatively well recognized. At the same time, little attention has been paid to the overall water resources and the conditions of their formation, and also relations between average values of precipitation and runoff in KV. This is all the more important, since that area plays a key role in the formation of water resources in western Poland, e.g. the water supply systems in Wroclaw city depend on the Nysa Kłodzka River (through the water transfer to the Oława River) (Olichwer 2018). Besides, in the previous analyses, the role of share of individual sub-catchments in the formation of the KV water resources has not been determined yet.

This study aims to fill in the above-mentioned research gap and identify hydro-meteorological relationships at three different levels, namely: (1) between precipitation recorded at individual rain gauge stations with precipitation in the entire upper Nysa Kłodzka River catchment, (2) between runoff from the individual sub-catchments with runoff from the whole Nysa Kłodzka River catchment, and (3) between precipitation and runoff in the respective sub-catchments, and runoff from the entire Nysa Kłodzka River catchment. Additionally, methodology applied in the analysis was clearly different from that employed by other authors in previous studies on hydrology of KV, as the use was made of the bivariate Archimedean copulas. Copula functions are becoming more and more popular tools in hydrological research, and some successful applications include papers e.g. of Xing et al. (2015) and Fan et al. (2017).

This study is a continuation of the research carried out by Perz et al. (2021), who determined the degree of synchronicity between precipitation and runoff in KV. It should be underlined that despite a relatively small area of KV this research goes far beyond the local scale, because the proposed methodology allows determining relationships between elements of the water balance in different catchments, regardless of their size, climate and geographical position. Besides a purely scientific significance, our study has also a considerable practical added value, as the proposed methodology can be applied in determining dependencies between selected elements of the water balance.
and evaluation of water resources availability in mountain catchments.

**Study area and methods**

**Study area**

The study area is situated in south-western Poland, in the upper Nysa Kłodzka River catchment, controlled by gauge Kłodzko (Fig. 1). In terms of geology, KV is a longitudinal tectonic ditch, separating the Central and Eastern Sudetes (Kondracki 2013). To the west KV borders with the Bystrzyckie Mountains, and to the east with the Śnieżnik Massif, the Złote Mountains, and the Bardzkie Mountains. The northern border of the study area is not clearly defined, and the Lower Ścinawka River and the Noworudzkie Lowering are considered extensions of KV (Kondracki 2013). The study area shows considerable differences in altitude: its highest point is the Three-seas Peak (1145 m a.s.l.), while the lowest is located in the Kłodzko town (280 m a.s.l.) (Fig. 1). KV has an undulating and hilly mid-mountain relief, the important features of which are clearly marked morphologically river valleys and various stages of development of the river channel system (Szalińska et al. 2008). Its geology exhibits little variability; the research area is mainly built of the pre-Cambrian metamorphic rocks and sedimentary rocks of the Cretaceous period (Szalińska et al. 2008).

The 182-km long Nysa Kłodzka is the trunk river of KV. It is the left tributary of the Odra (Oder) River, which is the second-longest river of Poland. The Nysa Kłodzka River originates on the slopes of the Three-seas Peak. Initially, the river runs along the Upper Nysa Ditch, which is its natural drainage channel (Staffa 1993). Then, it cuts through KV as a mountain river, and after breaking through the Bardo Mountains it flows from the study area and becomes a meandering, lowland river. Its main tributaries in KV are: the Wiłecka (18.2 km), Bystrzyca (25.5 km), Biała Łądecka (52.7 km), and Bystrzyca Dusznicka (33 km) rivers. Their regime is nival-pluvial and pluvial-nival (Wrzesiński 2016, 2021). According to Perz (2019), rivers of KV have two of five types of regimes: type 2—nival moderately developed

![Fig. 1 Location of the water and rain gauges, boundaries of analysed catchments and geographical position of the study area in Poland](image)
(the upper section of the Nysa Klodzka above gauge Międzylesie, the Bystrzyca and the Bystrzyca Dusznicka rivers), and type 4—nival-pluvial regime (the Nysa Klodzka River below gauge Międzylesie, the Biała Łądecka and Wilczka rivers) (Fig. 1, Table 2).

The KV rivers are susceptible to catastrophic floods triggered by sudden or prolonged rainfall and thaws, and enhanced by a large gradient of the river channels, and also the topography and geology of the sub-catchments. For example, studies of Rutkowska et al. (2016) reveal that the subsoil in the Bystrzyca River sub-catchment is largely made of low-thickness loams with moderate water permeability, which contributes to increasing surface runoff and faster formation of flood waves. Among the most disastrous floods in KV, the “millennium flood” in July 1997 resulted in a huge material losses and a number of victims not only in the Klodzko region, but also in areas located along the Odra River, including the city of Wrocław.

According to RZGW in Wrocław (2013), the upper part of the Nysa Klodzka River catchment is situated in the so-called Klodzko climatic region of the Sudetes climate district. The lowest annual average temperature (4.9 °C) in KV is recorded in the Bystrzyckie Mountains, while the highest (above 8 °C) in the foreland of the Opawskie Mountains (RZGW in Wrocław 2013). Precipitation is differentiated spatially, with its relatively higher annual values in the mountainous southern, western and eastern parts of the study area, in particular in the Bystrzyca Dusznicka and Wilczka and the upper Biała Łądecka sub-catchment (Figs. 1, 2A). Noticeably lower precipitation is recorded in the less elevated, central and northern parts of KV (Fig. 2A).

Precipitation is also diversified in terms of the deviation of its values recorded at individual rain gauge stations in relation to the average precipitation in the whole catchment area (Fig. 2A); the highest annual precipitation totals are recorded in rain gauge station Zieleniec (1250.9 mm), while the lowest in Klodzko (591.4 mm) (Table 1). Moreover, precipitation in KV exhibits apparent variations on the multiannual and monthly bases.

Runoff in the whole Nysa Klodzka catchment controlled by gauge Klodzko is 382 mm (Table 2), and it is spatially diversified. Among the analysed sub-catchments, the highest runoff is typically recorded in the Wilczka River sub-catchment (740 mm), while the lowest in the Bystrzyca

### Table 1 Basic characteristics of analysed rain gauge stations in 1974–2013

| Rain gauge station | Coordinates | Altitude (m a.s.l.) | Precipitation (mm) |
|--------------------|-------------|---------------------|--------------------|
| Bielice            | 50° 16’ N 17° 00’ E | 695 | 1070.4 |
| Chocieszów         | 50° 27’ N 16° 29’ E | 405 | 694.3 |
| Klodzko            | 50° 26’ N 16° 29’ E | 356 | 591.4 |
| Międzygórze        | 50° 13’ N 16° 46’ E | 585 | 1035.9 |
| Międzylesie        | 50° 09’ N 16° 40’ E | 450 | 876.3 |
| Niemojów           | 50° 09’ N 16° 34’ E | 570 | 938.5 |
| Nowy Gierałtów     | 50° 18’ N 16° 57’ E | 635 | 984.0 |
| Oldrzycowice       | 50° 21’ N 16° 43’ E | 340 | 706.4 |
| Podzamek           | 50° 25’ N 16° 43’ E | 400 | 710.7 |
| Polanica-Zdrój      | 50° 25’ N 16° 31’ E | 390 | 712.5 |
| Zieleniec          | 50° 19’ N 16° 23’ E | 845 | 1250.9 |

Fig. 2 Average precipitation (A) and runoff (B) in sub-catchments of KV in 1974–2013. On map B values of the total runoff refer to differential catchments, for example, to calculate the total runoff in the Biała Łądecka River sub-catchment controlled by gauge Żelazno, runoff recorded in gauge Łądek-Zdrój was subtracted from that in gauge Żelazno. In turn, the percent share of surface and underground runoff in the total runoff is presented for the whole sub-catchment area controlled by a given water gauge, for example, the percent values calculated for gauge Żelazno refer to the Biała Łądecka River from its sources to gauge Żelazno—on the subsequent maps values for individual catchments are presented in the same manner, i.e. from the sources to the water gauge.
Dusznicka River sub-catchment (401 mm) (Table 2). Taking into account, the differential catchments (see explanation under the Fig. 2 caption), the lowest runoff is in the differential catchment of the Nysa Kłodzka River between gauges Bystrzyca Kłodzka II and Kłodzko (only 108 mm) (Fig. 2B).

Figure 2B also shows the runoff structure, divided into the surface and underground runoff. In most of the studied catchments the structure of runoff is similar—the percent share of the surface and underground runoff is about 50% each. However, the upper section of the Nysa Kłodzka River, controlled by gauges Międzylesie and Bystrzyca Kłodzka II, clearly differs from this pattern—in that area the surface runoff noticeably prevails, accounting for over 65% of the total runoff.

### Data sets

Values of precipitation and runoff collected in KV in the multi-annual period 1974–2013 are the basis of this research. The data were recorded at 11 rain gauge stations (Fig. 1, Table 1) and at eight water gauge stations (Fig. 1, Table 2).

It has to be noted that for the purpose of interpolation of the average precipitation totals, data from the Niemojów rain gauge station were used, however, they were not included in the synchronicity analysis because of location of that gauge beyond the analysed area (Fig. 1).

All data sets were obtained from the resources of the Institute of Meteorology and Water Management—National Research Institute in Warsaw, Poland.

### Methods

#### Interpolation of data

Precipitation values were interpolated using open-source R package MACHISPLIN (Brown 2020). This R package interpolates noisy multivariate data through machine learning ensembling of up to six algorithms: boosted regression trees, neural networks, generalized additive model, multivariate adaptive regression splines, support vector machines, and random forests. It allows to simultaneously evaluate different combinations of the six algorithms to predict the input data. During model tuning, each algorithm is systematically weighted from 0 to 1 and the fit of the ensembled model is evaluated. The best performing model is determined through k-fold cross validation ($k = 10$) and the model that has the lowest residual sum of squares of test data is chosen. After determining the best model algorithms and weights, a final model is created using the full training dataset. Residuals of the final model are calculated from the full training dataset and these values interpolated using thin-plate-smoothing splines. This creates a continuous error surface and is used to correct most the residual error in the final ensemble model (Brown 2020). Such a described method (based on machine learning algorithms) has been used in recent research regarding precipitation interpolation and found to be reliable (Guo et al. 2020).

In the first step, the annual values of precipitation recorded in 1974–2013 at individual rain gauge stations were transferred into a shapefile, in which each of the stations was properly designated spatially. Then, the precipitation data were interpolated, separately for each year. In that way, 40 raster files were obtained, covering the area larger than KV. Each of them was used to receive the areal sum of precipitation, independently for each analysed sub-catchment (Fig. 1, Table 2). The calculated in this way areal annual precipitation totals were then arranged in the chronological data sequences, reflecting the variability of precipitation in 1974–2013, used in further analyses.

Synchronicity values were interpolated using simpler method, i.e. the Inverse Distance Weighted (IDW) interpolation method. This method is based on the functions of the

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Table 2: Basic characteristics of analysed river gauges in 1974–2013

| River    | Gauge            | Coordinates | Altitude (m a.s.l.) | Catchment area (km²) | Runoff depth (mm) | Areal precipitation1 (mm) | River regime type² |
|----------|------------------|-------------|---------------------|----------------------|-------------------|--------------------------|-------------------|
| Nysa Kłodzka | Międzylesie    | 50° 09' N 16°39' E | 426                | 49.7                 | 458.7           | 893.8                  | 2                 |
|          | Bystrzyca Kłodzka II | 50° 17' N 16°39' E | 338                | 260.0                | 482.3           | 898.6                  | 4                 |
|          | Kłodzko          | 50° 26' N 16°39' E | 281                | 1084.0               | 381.6           | 891.7                  | 4                 |
| Wilczka  | Wilkanów         | 50° 14' N 16°41' E | 363                | 35.1                 | 739.8           | 1036.5                 | 2                 |
| Bystrzyca| Bystrzyca Kłodzka I | 50° 17' N 16°39' E | 340                | 64.0                 | 496.2           | 1056.8                 | 2                 |
| Biała Lądecka | Łądek Zdrój   | 50° 20' N 16°52' E | 421                | 166.0                | 655.4           | 1021.9                 | 4                 |
|          | Żelazno          | 50° 22' N 16°40' E | 317                | 305.0                | 511.9           | 959.3                  | 4                 |
| Bystrzyca Dusznicka | Szalejów Dolny | 50° 25' N 16°34' E | 305                | 175.0                | 401.1           | 901.4                  | 2                 |

1 Acquired by MACHISPLIN interpolation—for details see Sect. “Interpolation of data”
2 Types of river regime: 2—nival moderately developed, 4—nival-pluvial (Source: Perz 2019; Wrzesiński 2016, 2021, modified)
inverse distances, in which the weights are defined by the opposite of the distance and normalized, so that their sum equals one (Ly et al. 2013). The weights decrease with the increase of the distance.

**Synchronous and asynchronous occurrence**

In this study, the two-dimensional (bivariate) Archimedean copula functions have been used. Copulas have been defined by Sklar (1959), as a joint distribution function of standard uniform random variables. Copulas are proven as a powerful tool for multivariate analysis of nonlinearly interrelated hydrological and meteorological data (Fan et al. 2017). The Copula functions have been widely applied in hydrological analyses, including recent studies on synchronicity of the maximum runoff and its spatial differentiation in the Warta River catchment (Perz et al. 2020), synchronicity of the maximum and mean flow in the Upper Indus River Basin (Sobkowiak et al. 2020), and the rainfall–runoff relations in the Nysa Kłodzka River catchment in Poland (Perz et al. 2021).

In the research, copulas have been applied to analyse the synchronicity and asynchronicity (probability of synchronous and asynchronous occurrence) between:

- Precipitation totals recorded in rain gauge stations ($P_{\text{RGS}}$) and average areal precipitation totals for the whole KV ($P_{\text{KV}}$), acquired through interpolation (see Sect. “Interpolation of data”)—results are presented in Sect. “Synchronicity of precipitation”;
- Runoff totals recorded in sub-catchments ($R_{\text{SC}}$) and runoff totals recorded in water gauge Kłodzko ($R_{\text{KV}}$ describing KV as a whole)—results are presented in Sect. “Synchronicity of runoff”;
- Areal precipitation totals acquired through interpolation for each sub-catchment ($P_{\text{SC}}$) and runoff: (1) recorded in water gauge closing the same sub-catchment ($R_{\text{SC}}$), and (2) recorded in water gauge Kłodzko ($R_{\text{KV}}$)—results are presented in Sect. “Synchronicity of precipitation and runoff”.

The first step was to select the best matching statistical distributions (among Weibull, Gamma, Gumbel, and log-normal) for the analysed data sets. To estimate values of distribution parameters the maximum likelihood method was used. The goodness-of-fit was checked with the help of the Akaike information criterion (AIC) (Akaike 1974):

$$\text{AIC} = N \log(\text{MSE}) + 2(\text{No. of fitted parameters}),$$  \hspace{1cm} (1)

where MSE is the mean square error, and $N$ is the sample size, or

$$\text{AIC} = -2 \log(\text{maximum likelihood for model}) + 2(\text{No. of fitted parameters}).$$ \hspace{1cm} (2)

The distribution type with the minimum AIC value is the best fitted (Akaike 1974).

In the next step, the joint distribution of compared data sets was constructed. It was made for paired data sets mentioned in bullets above. Analysis was made only for pairs of hydrologically connected precipitation and runoff data sets, to avoid a situation in which accidental statistical relations would be analysed.

In general, a bivariate Archimedean copula can be defined as:

$$C_\theta(u, v) = \phi^{-1}(\phi(u) + \phi(v)),$$ \hspace{1cm} (3)

where $u$ and $v$ are marginal distributions, the $\theta$, subscript of copula $C$, is the parameter hidden in the generating function $\phi$, and $\phi$ is a continuous function called a generator that strictly decreases and is convex from $I = [0,1]$ to $[0, \phi(0)]$ (Nelsen 1999).

Many copulas belonging to the Archimedean copula family can be used when the correlation between analysed data sets is both positive or negative, what was proved e.g. by Genest and Favre (2007). For this reason, the Clayton, the Gumbel–Hougaard and the Frank copula families (which are one-parameter Archimedean copula functions) were applied in this research. Equations of copula functions, parameter space, generating function $\phi(\cdot)$, and functional relationship of Kendall’s $\tau(\cdot)$ with a copula parameter for selected single-parameter bivariate Archimedean copulas can be found e.g. in paper of Perz et al. (2021).

The AIC was used to select the best-fitted joint distribution through comparison to the empirical joint distribution.

For each pair of compared data series, 5000 hypothetical values were generated at random, on the basis of previously computed statistical distribution parameters of marginal data sets. These values were used for selecting of the best-fitted copula family for each pair of compared data sets and, in consequence, for the forming of an appropriate function.

The above-described steps resulted in calculating the synchronicity and asynchronicity, i.e. the degree of probable synchronous and asynchronous occurrence, of compared data sets. The generated hypothetical value pairs were analysed in terms of $62.5\%$ and $37.5\%$ probability levels (Gu et al. 2018; Zhang et al. 2014), what led to designation of nine sectors (Table 3). These sectors show different relations between calculated probable values of compared data sets—three sectors (No. 1, 5, 9) with the synchronous occurrences and six sectors (No. 2, 3, 4, 6, 7, 8) with the asynchronous occurrences of compared data sets were designated (Table 3).
The degree of synchronicity (e.g. between compared precipitation and runoff data sets) is the percentage share of generated points in sectors 1, 5, and 9 in total amount of generated points. The asynchronicity was divided into two types:

- Moderate, which shows “low-medium”, “medium–low”, “medium–high” and “high-medium” relations (sectors 2, 4, 6, 8) and
- High, which shows “high-low” and “low–high” relations (sectors 3 and 7).

In other words, the synchronicity and asynchronicity (i.e. probability of synchronous and asynchronous occurrences) of analysed variables were determined through a calculation of threshold values of probability ranges:

- Probable values with a probability of exceedance of <62.5% were designated as LA/LB;
- Probable values with a probability of exceedance in a range >62.5% and <37.5% were designated as MA/MB;
- Probable values with a probability of exceedance >37.5% were designated as HA/HB.

The sum of degrees of synchronicity and asynchronicity is always 100%.

For example, the occurrence of “high” areal precipitation in a given sub-catchment (HPSc) is a synchronous event if in the same time unit “high” runoff from the sub-catchment (HRSc) occurs.

If the synchronicity of PSc and RSc in a given catchment is 70%, this means that in seven out of ten years, the probable PSc is within the same probability range as the probable RSc.

In turn, the asynchronous event can be exemplified by the occurrence of HPSc (e.g., a “20-year precipitation”, p = 5%) and the occurrence of LRSc (e.g., at the level of exceedance probability p = 80%) in the same catchment. As in example above, if the synchronicity is 70%, so the asynchronicity is 30%, what means that statistically the asynchronous event should occur average three times for every ten years.

In the “Results” section, the term “synchronicity”/“asynchronicity” refers to the synchronous/asynchronous occurrence (co-occurrence probability) of the analysed values.

### Results

#### Synchronicity of precipitation

The spatial analysis of the obtained results of the PRGS and PKV synchronicity reveals to what extent precipitation in individual rain gauges is similar to the areal average precipitation in the whole upper Nysa Kłodzka River catchment controlled by gauge Kłodzko in the following years of the analysed multi-annual period. The strongest synchronicity with PKV occurs in rain gauges located in the southern (Międzyglesie) and central (Ołdrzychowice) parts of the Nysa Kłodzka catchment (Fig. 3). This means that precipitation in these areas is not so much close to the average value, more in the same probability ranges (see Sect. “Synchronicity and asynchronicity occurrence”). The most synchronous in relation to PKV is precipitation at gauge Międzyglesie (> 75%) (Fig. 3). On this basis, it can be concluded that precipitation recorded at that gauge station best reflects the precipitation distribution in a given year in the whole Nysa Kłodzka catchment controlled by gauge Kłodzko. What should be noted, Międzyglesie is also precipitation gauge where average precipitation is the closest to areal precipitation from

| Sector   | X       | Y       |
|----------|---------|---------|
| 1        | LA–LB   | X ≤ A62.5% | Y ≤ B62.5% |
| 2        | LA–MB   | X ≤ A62.5% | B62.5% < Y ≤ B37.5% |
| 3        | LA–HB   | X ≤ A62.5% | Y > B37.5% |
| 4        | MA–LB   | A62.5% < X ≤ A37.5% | Y ≤ B62.5% |
| 5        | MA–MB   | A62.5% < X ≤ A37.5% | B62.5% < Y ≤ B37.5% |
| 6        | MA–HB   | A62.5% < X ≤ A37.5% | Y > B37.5% |
| 7        | HA–LB   | X > A37.5% | Y ≤ B62.5% |
| 8        | HA–MB   | X > A37.5% | B62.5% < Y ≤ B37.5% |
| 9        | HA–HB   | X > A37.5% | Y > B37.5% |

Where X = the value of variable A with a probability of exceedance >62.5%, A62.5%/B62.5% = the value of variable A or B with a probability of exceedance of 62.5%, A37.5%/B37.5% = the value of variable A or B with a probability of exceedance of 37.5%, L = “low”, M = “medium”, and H = “high”. A/B = variables analysed in this research, i.e. precipitation or runoff (see details on the beginning of this section).
the entire area—see Fig. 2A. On the other hand, the most asynchronous with $P_{KV}$ is precipitation recorded at rain gauge Polanica-Zdrój (39.8% probability of asynchronous situation), located in the Bystrzyca Dusznicka River sub-catchment. In this part of the study area, relatively high asynchronicity (31.5%) has also been concluded for rain gauge Zieleniec.

It is worth noting that precipitation in the upper reaches of the Biała Łądecka River sub-catchment (gauges Nowy Gierałtów and Bielice) is also less synchronous with $P_{KV}$ (Fig. 3). High values of moderate asynchronicity in these gauges indicate the possibility of relatively frequent occurrence of the "low-medium", "medium–low", "high-medium" and "medium–high" dependencies, while for example in most of the study area precipitation is close to the average values ($p \sim 50\%$), and high precipitation occurs in the Biała Łądecka River sub-catchment (e.g. $p = 10\%$).

However, high asynchronicities reach low values (1–3.6%) in the analysed rain gauges, except for rain gauge Polanica-Zdrój, where they reach 8% (Fig. 3). This means that despite some differences in the precipitation patterns in the study area, occurrence of the "low–high" and "high–low" dependencies is very unlikely, in other words, there are no areas in KV where precipitation could be extremely different from $P_{KV}$—of course, in terms of probable values, as there are significant differences in the average annual precipitation totals in the study area (see Fig. 2A).

**Synchronicity of runoff**

The synchronicity of $R_{SC}$ and $R_{KV}$ is relatively diversified and ranges from 56.9 to 68.4%. The least synchronous with $R_{KV}$ is runoff in the upper Nysa Kłodzka River catchment controlled by gauge Bystrzyca Kłodzka II (Fig. 4). This proves the relatively greater impact of the Nysa Kłodzka tributaries on the inter-annual variability of runoff in the whole Nysa Kłodzka catchment (at the closing gauge Kłodzko), and thus on the formation of water resources in the whole study area. In this context, the Biała Łądecka River plays a special role—relatively high
synchronicity (Łądek-Zdrój—68.4%, Żelazno—66.5%, see Fig. 4) indicates that in every seven years, the total runoff from this sub-catchment is within the same probability range as $R_{KV}$. It proves that the sub-catchments of the eastern tributaries are predominantly responsible for the formation of water resources in KV, in other words, that the runoff potential of the Biała Łądecka and Wilczka sub-catchments is much greater than that of the left tributaries of the Nysa Kłodzka—the Bystrzyca and Bystrzyca Dusznicka rivers, and even of the upper Nysa Kłodzka catchment itself.

It is also worth noting that in the upper part of the Nysa Kłodzka River, the synchronicity decreases along with the river course (Fig. 4)—the situation in the differential catchment area between gauges Międzylesie and Bystrzyca Kłodzka II has to be significantly different, even despite the inflow of the Wilczka River, the runoff of which is relatively synchronous with $R_{KV}$. A different way of shaping the runoff conditions in the southern part of the study area in a given year is also evidenced by the value of high asynchronicity of $R_{KV}$ with the section of the Nysa Kłodzka River catchment controlled by gauge Bystrzyca Kłodzka II (9.2%)—this means that almost every 10 years dependencies such as "low–high" or "high-low" may occur. This can be exemplified by the runoff in the upper part of the Nysa Kłodzka River catchment significantly below the average values, and in gauge Kłodzko definitely above them.

**Synchronicity of precipitation and runoff**

In the study area, the analysis of the precipitation-runoff relationships allowed determining both the strength of these relations (the degree of synchronicity between $P_{SC}$ and $R_{SC}$) in individual sub-catchments, and relationships between precipitation in each sub-catchment with the total runoff at gauge Kłodzko controlling the upper Nysa Kłodzka catchment ($P_{SC}$ and $R_{KV}$). The weakest relationship between $P_{SC}$ and $R_{SC}$, reflected in the lowest (46.2%) synchronicity between these variables, was recorded in the Bystrzyca River.
sub-catchment (gauge Bystrzyca Kłodzka I)—see Fig. 5. In the rest of the sub-catchments, the values of synchronicity between \( P_{SC} \) and \( R_{SC} \) are varied and range from 53.9 to 64.0%. The strongest precipitation-runoff relationships in sub-catchments, expressed as the synchronicity between these variables higher than 60%, were determined for the upper Biała Łądecka River (controlled by gauge Łądek-Zdrój) and Bystrzyca Dusznicka River (Szalejów Dolny). It has to be noted that the second highest synchronicity (63.3%) was detected between precipitation and runoff calculated for the whole KV (that is the \( P_{KV} – R_{KV} \) relationship).

These results indicate that response of individual sub-catchments to precipitation recorded in these sub-catchments is varied and may depend on local physiographic conditions. Moreover, the process of transformation of precipitation into runoff in these sub-catchments undergoes disturbances of different scale over the multi-annual period, which has impact on the differentiation of the obtained results of the \( P_{SC} – R_{SC} \) synchronicity.

Relationships between precipitation recorded in individual sub-catchments and runoff from the whole study area (that is between \( P_{SC} \) and \( R_{KV} \)) are spatially differentiated—see Fig. 5, refer to colours of the sub-catchments. The synchronicities between precipitation in the sub-catchments of the eastern tributaries of the Nysa Kłodzka River (the Biała Łądecka and Wilczka rivers) are more synchronous with \( R_{KV} \) than those in the sub-catchments of the western tributaries. \( P_{SC} \) in the upper Biała Łądecka River sub-catchment has the highest (63.7%) synchronicity with \( R_{KV} \), similarly to the \( R_{SC} – R_{KV} \) relationships (see Sect. “Synchronicity of runoff”). On the other hand, \( P_{SC} \) in the Bystrzyca River sub-catchment (gauge Bystrzyca Kłodzka I) shows the weakest co-occurrence probability, and therefore, the lowest (50.8%) synchronicity with runoff from the whole Nysa Kłodzka River catchment recorded in water gauge Kłodzko.

**Structure of water balance**

The structure of the water balance of the analysed sub-catchments is highly diversified and obviously related to the observed differences in their water abundance. For the whole Nysa Kłodzka catchment controlled by gauge Kłodzko,
the runoff coefficient, compared to other mountain areas in Poland, is relatively low (41.4%). Its highest values are characteristic for the most water-rich sub-catchments, with the highest average values of precipitation and runoff. This refers to the eastern sub-catchments of the Nysa Kłodzka tributaries, that is the Wilczka and Biała Łądecka rivers, controlled by gauge Łądek-Zdrój, where 66.7% and 61.3%, respectively of precipitation is transformed directly into the runoff—Fig. 6A. The lowest runoff coefficient value among the studied sub-catchments is determined for the Bystrzyca Dusznicka River sub-catchment, where the average runoff coefficient is below 44%. However, it should be noted that this is higher than for the entire study area (41.4%).

Determining the precipitation and runoff values with different probabilities of exceedance allowed for the analysis of changes in the structure of the catchment water balance, assuming a hypothetical situation of the occurrence of precipitation and runoff with the same probability of exceedance in one year—Fig. 6B–D. Higher precipitation and runoff result in an increased amount of rainwater transformed into outflow from the catchment area, evidenced by greater values of the runoff coefficients. The 10%, 1% and 0.2% exceedance probabilities of precipitation and runoff result in an increase of the runoff coefficients by 10%, 24% and 32%, respectively in the whole KV, and by 4–16%, 8–32% and 9–47%, respectively, in the sub-catchments (Fig. 6B–D). These increases are spatially diversified: they are the lowest in the sub-catchments of the Bystrzyca Dusznicka and Bystrzyca rivers, and the highest in the upper Nysa Kłodzka River catchment controlled by gauges Międzylesie and Bystrzyca Kłodzka II, and the eastern tributaries of the Nysa Kłodzka River. While in case of the Bystrzyca River sub-catchment these small changes in the runoff coefficient can be influenced by the lowest synchronicity between precipitation and runoff, the largest changes in the runoff coefficient in the upper Nysa Kłodzka catchment is probably influenced by different runoff structure, characterized by relatively the largest share of surface runoff in the total runoff (over 65%, see Fig. 2B).
Discussion

The research results confirm that conditions of the formation of key elements of the water balance (precipitation and runoff) and relations between them in the mountain catchment area are very complicated, determined both by the climatic factor and the physiographic characteristics of the catchment area. They made it possible to determine the following relationships in probabilistic terms:

- Between the in situ precipitation recorded in individual precipitation gauge stations with the averaged areal precipitation in the whole upper Nysa Kłodzka River catchment;
- Between runoff from the individual sub-catchments with the total runoff from the Nysa Kłodzka River catchment;
- Between the sub-catchment precipitation and runoff, and runoff from the whole Nysa Kłodzka River catchment;

This study is a part of research on the synchronous occurrence of hydro-meteorological phenomena. So far, analyses have been carried out to determine the degree of synchronicity in relationships between runoff and the volume of transported material (Guo et al. 2016; You et al. 2019; Zhang et al. 2014; Zhou et al. 2014), the occurrence of rainfall (Zhang et al. 2012) and runoff (Chen et al. 2018; Gu et al. 2018; Perz et al. 2020; Sobkowiak et al. 2020) or the water levels of coastal lakes and sea (Plewa et al. 2019), as well as the precipitation-runoff relationships (Perz et al. 2021). However, while these studies focussed mainly on one type of relationships, the presented methodology allowed for the simultaneous analysis of a number of relationships between precipitation and runoff, which then made it possible to examine thoroughly complex hydro-meteorological relationships in the research area.

The research shows that the precipitation relationships in the study area are clearly differentiated spatially. This is evidenced by significant deviations of the average precipitation observed at individual rain gauge stations from the precipitation value recorded for the whole catchment area, which constitute from only 66% (gage Kłodzko) to over 140% (gage Zielenevic) of the average precipitation (Fig. 2A). This has also been confirmed by the calculated \( P_{\text{RGS}} - P_{\text{KV}} \) synchronicity and asynchronicity indices. The method used allowed determining a rain gauge station that best reflects the average precipitation in the subsequent years of the multi-annual period in the whole Nysa Kłodzka River catchment—the amount of precipitation in gauge Międzyłesie is synchronous with the whole catchment rainfall in 75% (Fig. 3). The study has also showed that the degree of synchronicity between \( P_{\text{RGS}} \) and \( P_{\text{KV}} \) refers to the year-to-year variability of these variables, and is not necessarily related to the amount of precipitation. As a result, gauges with the largest deviations of precipitation from the average precipitation value for the whole KV (Fig. 2A) at the same time do not have to be characterized by the extreme values of the precipitation synchronicity (see Fig. 3).

The obtained results of the analysis of the runoff relationships in the sub-catchments with the total runoff of the Nysa Kłodzka controlled by gauge Kłodzko confirm that the total runoff in KV is most strongly influenced by the runoff from the Biała Łądecka River sub-catchment (Perz et al. 2021). At the same time, it is a sub-catchment with the largest water resources and a different distribution of runoff in the annual cycle. High summer rainfall totals are reflected in higher runoff during this season, which proves that river represents a nival-pluvial runoff regime (Perz 2019). As a result, after the inflow of the Biała Łądecka and Wilczka water, the Nysa Kłodzka River changes its runoff regime into this type. In the western part of the Nysa Kłodzka catchment, its tributaries (the Bystrzyca Dusznicka and Bystrzyca rivers) are supplied with the snowmelt water mainly in spring, and thus represent the nival type of regime. That variability of the runoff regimes in the Nysa Kłodzka River catchment results from both its geographical position and exposure of the sub-catchments, and also meteorological conditions triggering floods in the study area (Bednorz et al. 2019; Wrona 2008). The runoff regime characteristics of the KV rivers also show noticeable differences in terms of stability and uncertainty (Wrzesiński 2013, 2016). Rivers of the eastern part of the Nysa Kłodzka River catchment (Wilczka, Biała Łądecka) and the upper Nysa Kłodzka River are characterized by a relatively higher uncertainty of the runoff volume than those in its western part.

The research results prove a key importance of precipitation in the upper parts of the sub-catchments of the Nysa Kłodzka River and its eastern tributaries (in particular the Biała Łądecka River) in the formation of the total runoff in KV. It results both from higher precipitation totals in the higher parts of the mountain areas of KV (see Fig. 2A), and from the topography (higher elevation gradients) and the geological structure of these areas (Perz et al. 2021). This is confirmed by the analysis of the spatial variability of the runoff coefficient \( C \), also for the probable values of precipitation and runoff (see Fig. 6).

In general, the research results allow identification of sub-catchments particularly important in shaping the runoff conditions in KV. One of such areas is the upper Biała Łądecka River sub-catchment, which shows the strongest synchronicity in terms of the \( R_{\text{SC}} - R_{\text{KV}} \) (Fig. 4) and \( P_{\text{SC}} - R_{\text{KV}} \) (Fig. 5) relationships, despite the relatively lower \( P_{\text{SC}} - P_{\text{KV}} \) synchronicity (Fig. 3). This means that precipitation in this sub-catchment differ from the average precipitation in KV in the multi-annual period, but due to its size, it is largely responsible for the formation of the

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KV water resources. On the other hand, in the Bystrzyca Dusznicka River sub-catchment with the recorded highest sums of precipitation (Fig. 2A, Table 2), synchronicity of the $P_{SC} - P_{KV}$ relationships is even lower than in the upper Biała Łądecka River sub-catchment, and the $P_{SC} - R_{KV}$ synchronicity is the second lowest in the entire study area. This is due to a higher retention capacity and hydrological inertia of the Bystrzyca Dusznicka River sub-catchment compared to the Biała Łądecka River sub-catchment, which seems to be confirmed by low values of the runoff coefficient C (Fig. 6A) and its relatively small increase in the case of precipitation and runoff with a low probability of exceedance (Fig. 6C, D). In turn, changes in the value of the runoff coefficient in the Nysa Kłodzka River catchment controlled by gauges Międzylesie and Bystrzyca Kłodzka II are the largest among the analysed sub-catchments. This is due to the low retention capacity of that part of KV (sparse forest cover), which makes the share of surface runoff in the total runoff the highest (Fig. 2B), as the conditions are favourable for the transformation of rainfall into runoff.

The results obtained made it possible to indicate directions in the future research on relationships between selected hydro-meteorological variables with the use of the Copula function and the measure of synchronicity. One of them is an analysis based on monthly precipitation data, which would allow a detailed analysis of the pluvial regime. Another direction, due to the qualitative and quantitative differences in precipitation in individual seasons, would be the analysis of the precipitation-runoff relationships in the winter and summer half-years, respectively. Further analyses can also focus on the extreme values corresponding to high and low runoff of rivers—such studies could be a risk analysis related to the occurrence of floods or droughts in river catchments. Considerable potential lies also in the development of the method itself, for example, through the use of the multivariate Copula functions [such as in work of You et al. (2019)], as well as in exploring the problem of quantifying the uncertainty of the results generated by the constructed computational models, as indicated, among others, by Zhang et al. (2021). Uncertainty may concern both statistical side of the analysis, and the datasets, especially obtained through sophisticated interpolation methods—in such a case, the denser the network of water gauge stations, the lower the uncertainty of the calculated area precipitation should be.

In summary, KV is a hydrologically very active area with differentiated conditions of water circulation, which has also been confirmed by other studies (Olichwer 2018). Some researchers point to the growing importance of mountain water resources, as an increasing number of people living in lowlands depend on them (Viviroli et al. 2020). Thus, estimation of these resources is one of key challenges in modern hydrology and water resources management, especially in the conditions of a changing climate, as it can result not only in quantitative, but also qualitative shifts in precipitation (i.e. changes in the type of precipitation, with more precipitation falling in the form of rain instead of snow), disturbing the water balance in many foothill areas, as indicated, among others by Biemans et al. (2019).

**Conclusions**

To sum up, major findings of this research are as follows:

- Precipitation is spatially differentiated in KV, and areas with the most synchronous in situ precipitation with the average areal precipitation in the whole KV do not play the most important role in the formation of the KV water resources. The spatial distribution of the average areal precipitation in the Nysa Kłodzka River catchment controlled by gauge Kłodzko is best reflected in the Międzylesie rain gauge station.
- In terms of runoff the most synchronous with runoff from the whole KV are the sub-catchments with relatively poor synchronicity of in situ precipitation with average areal precipitation in KV—these are the sub-catchments of the Biała Łądecka and Bystrzyca Dusznicka rivers.
- The runoff coefficient is a useful tool to determine the structure of the water balance, to quantify the transformation of precipitation into runoff, and relations between these variables. Its values differ significantly in individual sub-catchments what is influenced by hydro-climatic conditions (precipitation and runoff values) and physical-geographical characteristics of a given catchment.
- This research confirmed the results of our earlier study, i.e. that the right tributaries of the Nysa Kłodzka River are generally more hydrologically active than the left ones, and that the regime characteristics of the KV rivers are shaped by the type and distribution of precipitation in the yearly cycle, and also its relationship with runoff. By calculating the precipitation in an individual sub-catchment, we eliminated one of the limitations of the previous study, i.e. the inability to analyse the precipitation-runoff relationship in the Bystrzyca River sub-catchment, caused by a lack of rain gauge station in that part of KV.

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**Availability of data and material** Data used in the manuscript were obtained from the databases of Institute of Meteorology and Water Management–National Research Institute in Warsaw, Poland. The calculation data can be obtained upon request from the corresponding author.

**Code availability** Code can be obtained upon request from the corresponding author.

**Declarations**

**Conflict of interest** On behalf of all authors, the corresponding author states that there is no conflict of interest.

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