Uniwersytet im. Adama Mickiewicza w Poznaniu

Wydział Nauk Geograficznych i Geologicznych

ROZPRAWA DOKTORSKA

mgr Adam Edmund Perz

Kopule w badaniach relacji zmiennych hydro-meteorologicznych oraz zagrożenia i ryzyka powodziowego w zlewni górnej Nysy Kłodzkiej

Copulas in studies of relationships of hydro-meteorological variables and flood hazard and risk in the upper Nysa Kłodzka catchment

Promotorzy:

prof. UAM dr. hab. Dariusz Wrzesiński

prof. dr. hab. Waldemar Budner

Rozprawa realizowana była w ramach projektu „GEO-INTER-APLIKACJE: wysokiej jakości program studiów doktoranckich realizowany na Wydziale Nauk Geograficznych i Geologicznych Uniwersytetu im. Adama Mickiewicza w Poznaniu nr POWR.03.02.00-00-I027/17”.

Poznań, czerwiec 2023 r.

Spis treści

Mojej Żonie Ani

Podziękowania

Powstanie rozprawy nie byłoby możliwe bez wsparcia finansowego i organizacyjnego projektu „GEO-INTER-APLIKACJE: wysokiej jakości program studiów doktoranckich realizowany na Wydziale Nauk Geograficznych i Geologicznych Uniwersytetu im. Adama Mickiewicza w Poznaniu nr POWR.03.02.00-00-I027/17”, realizowanego w ramach Programu Operacyjnego Wiedza Edukacja Rozwój. Bardzo dziękuję kierownikowi studiów prof. UAM dr. hab. Jackowi Michniewiczowi oraz innym osobom zaangażowanym w realizację projektu.

Trudno w krótkich słowach wyrazić wdzięczność za ogrom czasu, zaangażowania i cierpliwości oraz dyskusje, ukierunkowanie w działaniach i motywację, które zapewnił mi Promotor prof. UAM dr hab. Dariusz Wrzesiński. Pragnę także podziękować Promotorowi prof. dr. hab. Waldemarowi Budnerowi za czas, pomoc i krytyczne spojrzenie, tak potrzebne w realizacji badań naukowych. Bardzo Panom Profesorom dziękuję i mam nadzieję na dalszą naukową współpracę.

Dziękuję także pozostałym współautorom publikacji – prof. UAM dr. hab. Leszkowi Sobkowiakowi za pomoc merytoryczną i redakcyjną, ale i obecność w trakcie całego toku doktoratu, oraz dr. inż. Radosławowi Stodolakowi za podzielenie się swoją wiedzą o niuansach hydrologii obszaru badań. Dziękuję także wszystkim pracownikom Zakładu Hydrologii i Gospodarki Wodnej, Instytutu Geografii Fizycznej i Kształtowania Środowiska Przyrodniczego oraz Wydziału Nauk Geograficznych i Geologicznych za owocną współpracę, niejedno dobre słowo i konsultacje.

Studiów doktoranckich nie mógłbym zrealizować także bez wsparcia Koleżanek i Kolegów ze Sweco Polska, będącego interesariuszem doktoratu. Dzięki Waszej pomocy udało się wiele rzeczy usprawnić, a także zadbać o praktyczne aspekty badań.

Jestem również niezmiernie wdzięczny za dostrzeżenie i docenienie mojej pracy badawczej przez Fundację Uniwersytetu im. Adama Mickiewicza w Poznaniu, Poznański Park Naukowo-Technologiczny oraz Kulczyk Foundation oraz udzielenie przez te organizacje stypendiów, które są dla mnie niezwykłym wyróżnieniem, ale i dodają pewności co do słuszności obranej ścieżki i pozwoliły na skupienie się na realizacji doktoratu w kluczowych momentach.

Na koniec chciałbym złożyć prawdopodobnie najważniejsze podziękowania – mojej Żonie Ani, bez której cierpliwości, wsparcia w rzeczach małych i dużych oraz niejednego wyrzeczenia realizacja doktoratu nie miałaby szans powodzenia. Jestem wdzięczny całej Rodzinie i Przyjaciołom, a szczególnie Rodzicom i Rodzeństwu, za motywację i pomoc w stawianiu kolejnych kroków w realizacji rozprawy.

Dziękuję!

1 Wprowadzenie

Właściwością środowiska geograficznego jest występowanie relacji pomiędzy jego elementami, jak i zachodzącymi w nim procesami i zjawiskami. Rolą nauk geograficznych jest z kolei m.in. badanie tych relacji i zależności pod kątem siły czy przestrzennego zróżnicowania, a także ich miejsca i znaczenia w ciągach przyczynowo-skutkowych. Jednym z tych ciągów bez wątpienia jest obieg wody w przyrodzie. Główne elementy bilansu wodnego (tj. opady atmosferyczne, parowanie i odpływ) są ze sobą ściśle powiązane i oddziałują na siebie. Relacje te modyfikowane są przez inne cechy środowiska geograficznego, jak budowa geologiczna, ukształtowanie terenu, klimat, szata roślinna czy efekty działalności człowieka. Poznanie, opisanie i ilościowe ustalanie siły tych relacji jest kluczowe z poznawczego punktu widzenia, a także z uwagi na istotny potencjał aplikacyjny w gospodarce wodnej czy ochronie przeciwpowodziowej.

Potencjał ten wynika z kluczowego znaczenia wody dla życia na Ziemi, w tym i człowieka. Od tysięcy lat ludzkość stara się wykorzystywać i kształtować zasoby wodne, a także łagodzić skutki ekstremalnych zdarzeń hydro-meteorologicznych takich jak susze i powodzie. Poznanie praw rządzących obiegiem wody i umiejętność (lub jej brak) zastosowania ich do celów gospodarczych niejednokrotnie decydowały o powstaniu lub upadku państw i cywilizacji. Jednakże i dzisiaj, w dobie postępującej zmiany klimatu i rosnącej presji na środowisko przyrodnicze, kluczowe znaczenie dla gospodarki ma racjonalne korzystanie z zasobów wodnych oraz badanie i modelowanie zjawisk ekstremalnych w celu skutecznego zarządzania ryzykiem związanym z ich występowaniem.

Praca doktorska pt. „Kopule w badaniach relacji zmiennych hydro-meteorologicznych oraz zagrożenia i ryzyka powodziowego w zlewni górnej Nysy Kłodzkiej” mieści się w dziedzinie nauk ścisłych i przyrodniczych w dyscyplinie nauk o Ziemi i środowisku. Stanowi ona zbiór powiązanych tematycznie artykułów opublikowanych w recenzowanych czasopismach naukowych posiadających Impact Factor (IF). Sumaryczny IF przedstawionego zbioru (dla artykułu nr 1 zgodny z rokiem publikacji, a w przypadku artykułów nr 2-4 za rok 2021) wynosi 14,79, a suma punktów wg wykazu czasopism naukowych MEiN wynosi 370. We wszystkich artykułach doktorant jest głównym autorem i ma większościowy udział (75% lub więcej) w przeprowadzeniu badań i przygotowaniu publikacji oraz jest wskazany jako autor prowadzący korespondencję.

Artykuły wchodzące w skład rozprawy doktorskiej:

1. **Perz, A.***, Sobkowiak, L., Wrzesiński, D., 2021. Probabilistic Approach to Precipitation-Runoff Relation in a Mountain Catchment: A Case Study of the Kłodzka Valley in Poland. Water 13, 1229.
   (IF: **3.530**, lista MEiN: **100 pkt**, udział w powstaniu artykułu: 75%)

2. **Perz, A.***, Sobkowiak, L., Wrzesiński, D., 2022a. Co-occurrence probability of water balance elements in a mountain catchment on the example of the upper Nysa Kłodzka River. Acta Geophys 70, 1301–1315.
   (IF: **2.293**, lista MEiN: **70 pkt**, udział w powstaniu artykułu: 75%)

3. **Perz, A.***, Wrzesiński, D., Sobkowiak, L., Stodolak, R., 2022b. Copula-based geohazard assessment – case of flood-prone area in Poland. J Hydrology Regional Stud 44, 101214.
(IF: **5.437**, lista MEiN: **100 pkt**, udział w powstaniu artykułu: 80%)

4. **Perz, A.***, Wrzesiński, D., Budner, W.W., Sobkowiak, L., 2023. Flood-Triggering Rainfall and Potential Losses—The Copula-Based Approach on the Example of the Upper Nysa Kłodzka River. Water 15, 1958.
(IF: **3.530**, lista MEiN: **100 pkt**, udział w powstaniu artykułu: 80%)

* autor korespondencyjny

2 Koncepcja i cele rozprawy

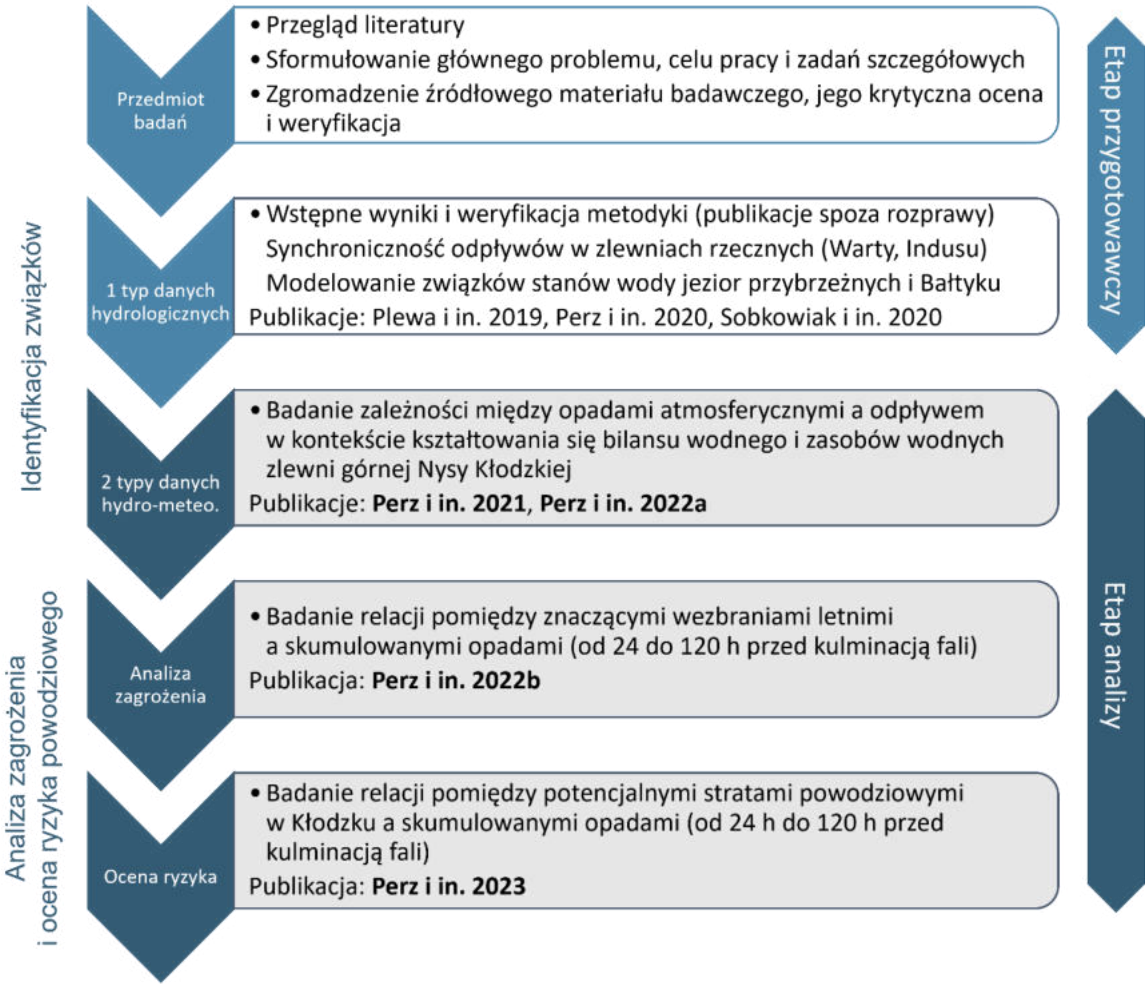
Przeprowadzenie badań zaprezentowanych w artykułach składających się na rozprawę doktorską zostało poprzedzone pracami przygotowawczymi (Ryc. 1), mającymi na celu weryfikację wybranej metodyki i przedstawienie wstępnych wyników analiz. Dotyczyły one relacji odpływów maksymalnych w zlewni Warty (Perz i in. 2020), przepływów średnich i maksymalnych w zlewni Indusu (Sobkowiak i in. 2020), a także stanów wody jezior przybrzeżnych i Morza Bałtyckiego (Plewa i in. 2019). Uzyskane rezultaty pozwoliły na wyciągnięcie wniosku o przydatności kopul i bazującej na nich miary siły związków w badaniu relacji zmiennych hydrologicznych w ujęciu probabilistycznym.

Problematyka badawcza rozprawy dotyczy zarówno relacji opadów atmosferycznych i odpływów rzecznych w ujęciu średniorocznym, jak i relacji opadów atmosferycznych i przepływów lub stanów wody w analizie zdarzeń ekstremalnych – wezbrań – w kontekście zagrożenia i ryzyka powodziowego. W pracy wykorzystane zostały zatem nie tylko zmienne hydrologiczne, jak na etapie przygotowawczym, ale także meteorologiczne i ekonomiczne. Obejmują one m.in. przepływ i odpływ rzeczny, parametry fal wezbraniowych, sumy opadów atmosferycznych i potencjalne straty powodziowe (Ryc. *2*). Głównym celem rozprawy jest **ustalenie w ujęciu probabilistycznym siły związków i ich zróżnicowania w czasie i przestrzeni między zmiennymi hydrologicznymi, meteorologicznymi oraz ekonomicznymi w zlewni górnej Nysy Kłodzkiej**. Przeprowadzone badania (Ryc. 1) dotyczą kształtowania się najważniejszych elementów bilansu wodnego tego obszaru i formowania jego zasobów wodnych (Perz i in. 2021, 2022a), jak i zagrożenia (Perz i in. 2022b) i ryzyka powodziowego (Perz i in. 2023).

Rozprawa ze względu na problematykę badawczą i zastosowane podejście metodyczne ma walory interdyscyplinarnej i oryginalnej pracy naukowej o istotnym potencjale aplikacyjnym w gospodarce wodnej obszaru badań. Osiągnięcie głównego celu rozprawy i określenie potencjału funkcji kopul w ustalaniu siły relacji typu opad-odpływ oraz zagrożenia i ryzyka powodziowego w ujęciu probabilistycznym w zlewni górnej Nysy Kłodzkiej możliwe było poprzez realizację szczegółowych zadań badawczych, które obejmują:

1. Ustalenie relacji opadów atmosferycznych i odpływu rzecznego oraz rozpoznanie ich przestrzennego zróżnicowania.
2. Ustalenie i zastosowanie obszarowych sum opadów atmosferycznych w badaniu relacji typu opad-odpływ.

3. Identyfikację letnich fal wezbraniowych i wezbraniogennych opadów atmosferycznych oraz określenie przestrzennego zróżnicowania siły związku opadów poprzedzających wezbranie z parametrami fal wezbraniowych: przepływem kulminacyjnym i objętością fali wezbraniowej.
4. Określenie siły relacji opadów atmosferycznych poprzedzających kulminacje fal powodziowych z wysokością potencjalnych strat powodziowych w Kłodzku.



Ryc. 1 Schemat postępowania badawczego

Objęta badaniami zlewnia górnej Nysy Kłodzkiej od źródeł po wodowskaz Kłodzko to hydrologicznie interesujący obszar, który z jednej strony pełni istotną rolę w kształtowaniu zasobów wodnych dorzecza Odry, a z drugiej narażony jest na powodzie, będące konsekwencją górskiego charakteru cieków oraz koncentrycznego układu sieci rzecznej. Dotychczasowe badania hydrologiczne tego obszaru skupiały się głównie na analizie powodzi historycznych i ich skutkach (np. Szalińska i in. 2008, Kundzewicz i in. 2009, Łach 2009, 2012, Bednorz i in. 2019), modelowaniu wezbrań na ciekach przedmiotowej zlewni (np. Rutkowska i in. 2016, Niedzielski, Miziński 2017, Jeziorska, Niedzielski 2018, Stodolak i in. 2018), a w mniejszym stopniu na zasobach wodnych tego obszaru (np. Mućka i in. 1998, Tokarczyk i in. 2007, Olichwer 2018). Publikacje składające się na rozprawę wpisują się w powyższe obszary badawcze. Dzięki zastosowaniu jednolitej metodyki analizy związków, badania te kompleksowo przedstawiają relacje zmiennych hydro-meteorologicznych na tym terenie. Są także odpowiedzią na zidentyfikowane w poszczególnych artykułach luki badawcze, co stanowi również o oryginalności rozprawy.

	Tytuł artykułu	Dane	Badane relacje zmiennych	Pozostałe wyniki
Artykuł nr 1	Probabilistic Approach to Precipitation-Runoff Relation in a Mountain Catchment: A Case Study of the Kłodzka Valley in Poland	Okres analizy: 1974-2013 • roczne opady • roczne odpływy	1. P (posterunki) – R (wodowskazy)	Wartości prawdopodobne rocznych sum opadów i rocznych odpływów całkowitych
Artykuł nr 2	Co-occurrence probability of water balance elements in a mountain catchment on the example of the upper Nysa Kłodzka River	Okres analizy: 1974-2013 • roczne sumy opadów • roczne odpływy całkowite	1. P (posterunki) – P (obszarowy) 2. R (podzlewnie) – R (Kłodzko) 3. P (obszarowy w podzlewniach) – R (podzlewnie), R (Kłodzko)	Współczynnik odpływu dla wartości średniorocznych oraz prawdopodobnych
Artykuł nr 3	Copula-based geohazard assessment – case of flood-prone area in Poland	Okres analizy: 1971-2019 • daty wezbrań letnich (> $Q_{99\%}$) • przepływ kulminacyjny • objętość fali wezbraniowej • opady skumulowane (24-120 h przed wezbraniem)	1. Q kulminacyjny (Kłodzko) – Q (inne wodowskazy) 2. Q kulminacyjne – V fali wezbr. 3. Q kulminacyjne – P skumulowane 4. V fali wezbr. – P skumulowane	Statystyki i parametry wytypowanych wezbrań
Artykuł nr 4	Flood-Triggering Rainfall and Potential Losses – the Copula-Based Approach on the Example of the Upper Nysa Kłodzka River	Okres analizy: 1971-2021 • daty powodzi letnich (> stanu alarmowego w Kłodzku) • kulminacyjne stany wód w Kłodzku • opady skumulowane (24-120 h przed wezbraniem)	1. potencjalne straty powodziowe w Kłodzku – P skumulowane	Powierzchnie zalewu dla wytypowanych powodzi

Ryc. 2 *Zestawienie artykułów składających się na rozprawę wraz ze wskazaniem wykorzystanych danych, badanych relacji zmiennych oraz pozostałych wyników przedstawionych w publikacjach. Oznaczenia: Q – przepływ, R – odpływ, P – opad atmosferyczny, V – objętość.*

Rozprawa składa się ze zbioru czterech spójnych tematycznie artykułów opublikowanych w międzynarodowych recenzowanych czasopismach naukowych (z listy MEiN). Dwie pierwsze prace wchodzące w skład rozprawy (Perz i in. 2021, Perz i in. 2022a) dotyczą zależności pomiędzy opadem atmosferycznym a odpływem rzecznym i ich przestrzennego zróżnicowania w zlewni górnej Nysy Kłodzkiej (Ryc. *2*).

Trzecia praca (Perz i in. 2022b) poświęcona jest związkom parametrów znaczących wezbrań (tj. wysokości przepływu kulminacyjnego i objętości fali wezbraniowej) z sumami opadów atmosferycznych poprzedzających wezbranie (Ryc. *2*). Zastosowano w niej odmienne podejście do badania zagrożenia powodziowego, bazujące na analizie synchroniczności występowania wezbrań i opadów atmosferycznych poprzedzających kulminację fali powodziowej.

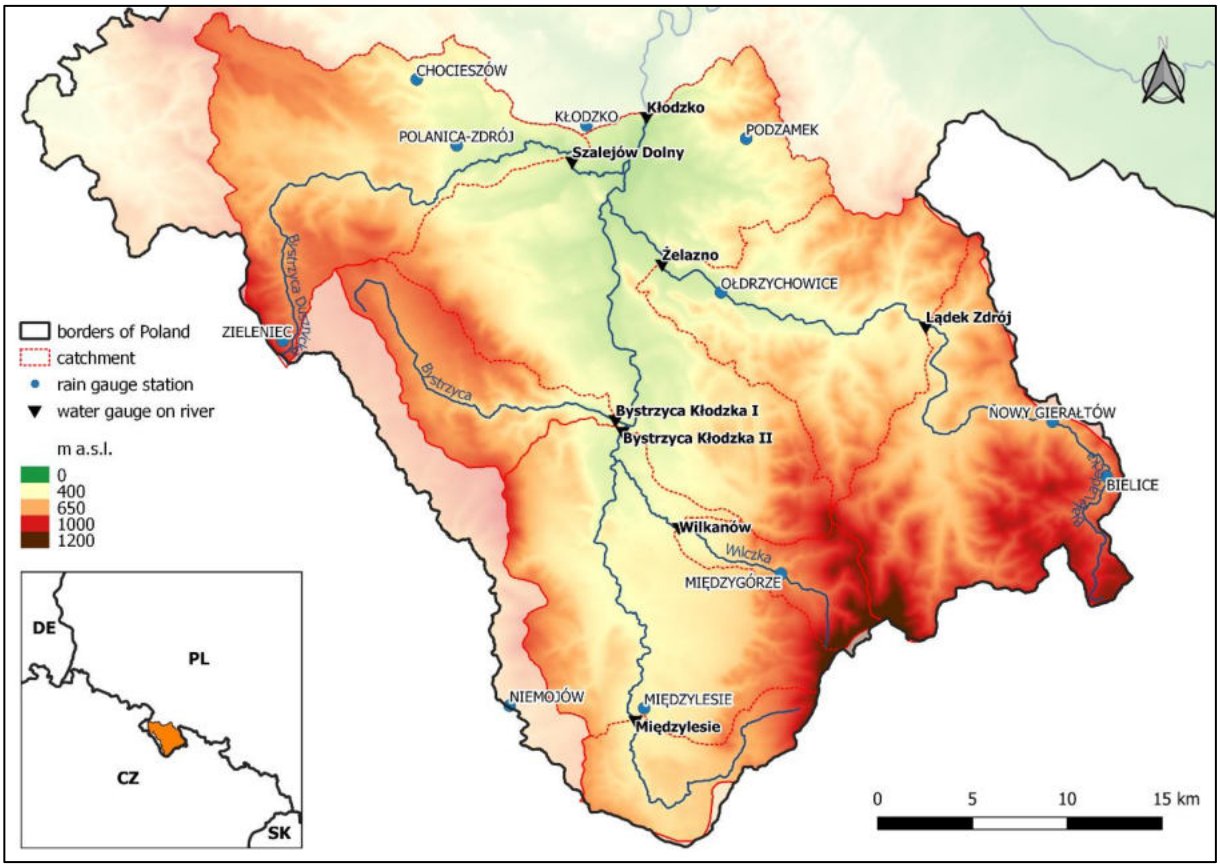
Czwarty artykuł (Perz i in. 2023) poświęcony jest zagadnieniu ryzyka powodziowego, wyrażonego potencjalnymi stratami powodziowymi (Ryc. *2*). W pracy zaproponowano metodykę badania probabilistycznych relacji między wysokością opadów atmosferycznych w zlewni górnej Nysy Kłodzkiej a potencjalnymi stratami powodziowymi w Kłodzku.

3 Obszar badań i źródła danych

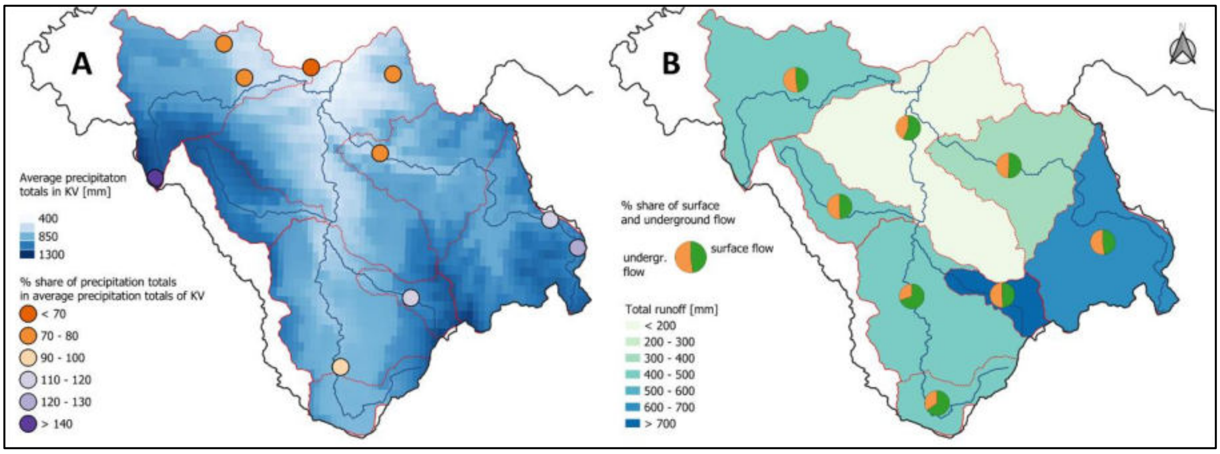
Jak wskazano we wprowadzeniu, przedstawiony zbiór publikacji jest spójny nie tylko pod względem tematyki i zastosowanych metod bazujących na teorii kopuli, ale i obszaru badań, którym jest zlewnia górnej Nysy Kłodzkiej po wodowskaz Kłodzko (Ryc. 3). W dotychczasowych publikacjach podkreślono, że jest to bardzo ważny obszar dla kształtowania się zasobów wodnych całego dorzecza Odry (Bednorz i in. 2019) czy zaopatrzenia w wodę m.in. Wrocławia (Olichwer 2018), ale także narażony na występowanie powodzi w wyniku ekstremalnych opadów atmosferycznych (Jania, Zwoliński 2011). Sprzyja temu koncentryczny układ sieci rzecznej (Bednorz i in. 2019), a możliwość nałożenia się fal wezbraniowych na Nysie Kłodzkiej i Odrze jest wymieniana jako jedno z najistotniejszych zagrożeń hydrologicznych w Polsce (Pociask-Karteczka i in. 2018). Jedną z największych współczesnych powodzi była tzw. „Powódź Tysiąclecia" w lipcu 1997 r., która pozbawiła życia kilku mieszkańców Kłodzka, a ok. 500 rodzin całego majątku (Kundzewicz i in. 2009).

Średnie sumy opadów atmosferycznych w zlewni górnej Nysy Kłodzkiej są przestrzennie zróżnicowane, z wyraźnie wyższymi wartościami na terenach wyżej położonych, tj. na zachodzie, południu i wschodzie obszaru, niższe sumy notowane są w części centralnej i północnej (Ryc. 4A). Opady atmosferyczne wykazują także zróżnicowanie pod względem odchylenia ich wartości na poszczególnych posterunkach opadowych w stosunku do średnich opadów w całej zlewni (Ryc. 4A). Najwyższe roczne sumy opadów notowane są na stacji opadowej Zieleniec (1250,9 mm), a najniższe w Kłodzku (591,4 mm) (Perz i in. 2022a).

Przestrzenne zróżnicowanie dotyczy także odpływu całkowitego (Ryc. 4B), który dla całego obszaru wynosi 382 mm (Perz i in. 2022a). Pośród zlewni cząstkowych obszaru najwyższy odpływ całkowity cechuje zlewnię Wilczki po Wilkanów (740 mm), a najniższy zlewnię Bystrzycy Dusznickiej po Szalejów Dolny (401 mm) (Perz i in. 2022a). W przypadku zlewni różnicowych najniższy odpływ ma fragment zlewni Nysy Kłodzkiej między wodowskazem Bystrzyca Kłodzka II a wodowskazem Kłodzko – jest to jedynie 108 mm (Ryc. 4B) (Perz i in. 2022a).



Ryc. 3 Obszar badań – zlewnia górnej Nysy Kłodzkiej po wodowskaz Kłodzko, z lokalizacją wodowskazów i zlewni cząstkowych oraz posterunków opadowych (Perz i in. 2022a)



Ryc. 4 Średnie roczne sumy opadów atmosferycznych (A) i średni roczny odpływ całkowity (B) w zlewniach cząstkowych obszaru badań (na podstawie danych z lat 1974-2013). Na mapie B wartości obliczone są dla zlewni różnicowych (Perz i in. 2022a)

Nysa Kłodzka i jej dopływy reprezentują różne typy reżimu odpływu. Wg klasyfikacji Dynowskiej (Dynowska, Pociask-Karteczka 1999) Nysa Kłodzka po Międzylesie oraz jej lewostronne dopływy – Bystrzyca i Bystrzyca Dusznicka – reprezentują reżim niwalny średnio wykształcony, a Nysę Kłodzką poniżej Międzylesia i jej prawe dopływy – Wilczkę i Białą Lądecką – charakteryzuje reżim niwalno-pluwialny (Perz 2019).

Wszystkie dane hydro-meteorologiczne wykorzystane w rozprawie pochodzą ze zbiorów Instytutu Meteorologii i Gospodarki Wodnej – Państwowego Instytutu Badawczego. W badaniach łącznie wykorzystano dane hydrometryczne (dobowe przepływy i stany wody) dla ośmiu wodowskazów z lat 1971-2021. Trzy wodowskazy zlokalizowane są na Nysie Kłodzkiej a pięć pozostałych na jej dopływach – Wilczce, Bystrzycy, Białej Lądeckiej i Bystrzycy Dusznickiej (Ryc. 3). Dane meteorologiczne pochodzą z jedenastu posterunków opadowych (Ryc. 3). W artykułach nr 1 i 2 (Perz i in. 2021, 2022a) dane te obejmowały lata 1974-2013, w artykule nr 3 (Perz i in. 2022b) okres pomiarowy wydłużono do lat 1971-2019, a w artykule nr 4 (Perz i in. 2023) do lat 1971-2021. W celu zgromadzenia możliwie największej liczby serii danych opadów atmosferycznych w pierwszych dwóch artykułach skrócono okres obserwacyjny do lat 1974-2013. W roku 2014 zaprzestano gromadzenia danych dla 5 posterunków: Podzamek, Bielice, Nowy Gierałtów, Chocieszów, Niemojów, a w roku 2016 dla Polanicy-Zdrój. Z kolei dane dla posterunku Zieleniec są dostępne dopiero od roku 1974. Wydłużenie serii danych w dwóch ostatnich artykułach wiązało się z przyjętą metodyką wyboru do analiz fal wezbraniowych – przeanalizowano wezbrania na rzekach od 1971 r. i okazało się, że po 2014 r. nie było wezbrań spełniających przyjęte kryteria. W związku z tym możliwe było uwzględnienie w badaniu posterunków opadowych, dla których przestano gromadzić dane po tym roku. Zgromadzone dane można uznać za wiarygodne – pozwalające na przeprowadzenie badań.

4 Metody badawcze

W każdym artykule podano szczegółowe informacje na temat źródeł, typu, zakresu czasowego i rozkładu przestrzennego wykorzystanych danych hydro-meteorologicznych oraz opisano zastosowane metody badawcze. Elementem łączącym wszystkie prace, oprócz obszaru badań, jest metodyka z zastosowaniem kopul i synchroniczności występowania zjawisk jako miary pozwalającej na badanie relacji między wybranymi zmiennymi.

Koncepcja kopuli została przedstawiona przez Sklara (1959), który zdefiniował ją jako funkcję łącznego rozkładu zmiennych. Kopula jest funkcją pozwalającą wydzielić z dystrybuanty łącznego rozkładu wektora losowego składową opisującą jedynie strukturę zależności (Doman 2011). Kopule umożliwiają ustalenie relacji między ciągami danych o odmiennych rozkładach statystycznych – w przeciwieństwie do wielu innych miar korelacji, które wymagają przyjęcia założenia o rozkładzie eliptycznym (normalnym lub *t* Studenta) (Doman 2011). Ciągi danych hydro- i meteorologicznych, szczególnie dotyczące ekstremów, rzadko reprezentują ten rodzaj rozkładu, a obliczanie współczynnika korelacji liniowej dla takich ciągów może być obarczone błędem (Doman 2011). Kopule pierwotnie znalazły szerokie zastosowanie w ekonomii i finansach (Frees, Valdez 1998, Genest et al. 2009, Kharoubi-Rakotomalala, Maurer 2013), m.in. w modelowaniu dynamiki zależności na rynkach finansowych (np. Doman 2011) czy w badaniu ryzyka kredytowego lub rynkowego (np. Lin et al. 2019). Z uwagi na swoje właściwości, zaczęto je stosować także do badania zależności pomiędzy danymi hydro-, meteo- i klimatologicznymi (np. De Michele, Salvadori 2003, Genest, Favre 2007).

Procedura analiz statystycznych, będąca częścią wspólną wszystkich załączonych artykułów, której wynikiem są wartości synchroniczności występowania zjawisk, tj. prawdopodobieństwa wystąpienia dwóch badanych zmiennych w tych samych przedziałach prawdopodobieństwa objęła następujące kroki:

- dla każdego szeregu danych dokonano wyboru najlepiej dopasowanego typu rozkładu statystycznego spośród czterech typów rozkładów, tj. Gumbela, Gamma, Weibull'a i logarytmiczno-normalnego, wykorzystując do tego kryterium informacyjne Akaikego (ang. *Akaike Information Criterion, AIC*) (Akaike 1974). Parametry tych rozkładów oszacowano metodą największego prawdopodobieństwa (Zhao i in. 2012). Najlepiej dopasowanym rozkładem jest ten, dla którego AIC przyjmuje najniższą wartość.

- Konstrukcja rozkładu łącznego dla badanych szeregów danych. W tym celu wykorzystano jednoparametryczne, dwuwymiarowe archimedesowe kopule z rodzin Claytona, Gumbela-Hougaarda i Franka (Tab. 1). Parametry funkcji zostały oszacowane wykorzystując estymatory największej wiarygodności (ang. *Maximum Likelihood Estimator, MLE*) (AghaKouchak, Nasrollahi 2010). Rozkład łączny najlepiej dopasowany został wybrany za pomocą AIC (Akaike 1974).

Tab. 1 Kopule i ich parametry, funkcja generująca ϕ(t) i zależność parametru od τ_θ Kendalla dla wybranych rodzin dwuwymiarowych kopul (za Doman 2011, Perz i in. 2021, Perz i in. 2022b)

Rodzina funkcji	$C_\theta(u,v)$	Generator $\phi(t)$	Parametr $\theta \in$	τ_θ Kendalla
Claytona	$max\left(\left(u^{-\theta}+v^{-\theta}-1\right)^{-1/\theta},0\right)$	$\frac{1}{\theta}\left(t^{-\theta}-1\right)$	$[-1,\infty)\backslash\{0\}$	$\tau=\theta/(2+\theta)$
Gumbela-Hougaarda	$exp\left\{-\left[(-ln\,u)^{\theta}+(-ln\,v)^{\theta}\right]^{1/\theta}\right\}$	$(-\ln t)^{\theta}$	$[1,\infty)$	$(\theta-1)/\theta$
Franka	$\frac{-1}{\theta}ln\left[1+\frac{\left(e^{-\theta_u}-1\right)\left(e^{-\theta_v}-1\right)}{e^{-\theta}-1}\right]$	$-ln\frac{e^{-\theta t}-1}{e^{-\theta}-1}$	$(-\infty,\infty)\backslash\{0\}$	$1+4[D_1(\theta)-1]/\theta$

gdzie $D_k(x)$ jest funkcją Debye'a, dla każdej pozytywnej liczby całkowitej k, $D_k(x)=\frac{k}{k^x}\int_0^x\frac{t^k}{e^t-1}dt$.

Dla wszystkich porównywanych szeregów danych, bazując na wcześniej obliczonych parametrach rozkładu statystycznego i rozkładzie łącznym, wygenerowano 5000 losowych punktów. Wartości te zostały wykorzystane do wyboru najlepiej dopasowanej rodziny kopuli niezależnie dla każdej z analizowanych par danych. Dzięki takiemu podejściu (tj. braku przyjęcia założenia o najlepszym dopasowaniu jednej rodziny kopuli dla wszystkich par szeregów danych) uniknięto wyników obarczonych poważnym błędem. Gu i in. (2018) udowodnili, że wybór nieodpowiedniej kopuli może prowadzić do wręcz odwrotnych rezultatów i wniosków niż w przypadku prowadzenia obliczeń w oparciu o najlepiej dopasowaną kopulę.

- Na podstawie poziomów prawdopodobieństwa 62,5% oraz 37,5% (Zhang i in. 2014, Gu i in. 2018), wyznaczono 9 sektorów (Tab. 2), które reprezentują różne typy relacji pomiędzy wartościami wygenerowanymi na podstawie porównywanych par danych. Trzy z nich reprezentują zdarzenia synchroniczne (nr 1, 5 i 9), natomiast pozostałe zdarzenia asynchroniczne (nr 2, 3, 4, 6, 7 i 8).

Łączny udział wygenerowanych punktów w sektorach 1, 5, 9 to wartość synchroniczności badanych zmiennych, natomiast asynchroniczność to udział punktów w pozostałych sektorach.

Można ją podzielić na umiarkowaną (sektory nr 2, 4, 6, 8) oraz wysoką (sektory nr 3, 7). Suma synchroniczności i asynchroniczności zawsze wynosi 100%.

Tab. 2 Wyznaczenie sektorów synchroniczności i asynchroniczności (za Perz i in. 2022a, Perz i in. 2022b, Perz i in. 2023, zmienione)

Sektor		Typ relacji zmiennych	X	Y
1	NA–NB	Synchroniczność	$X \leq A_{62.5\%}$	$Y \leq B_{62.5\%}$
2	NA–ŚB	Umiarkowana asynchroniczność	$X \leq A_{62.5\%}$	$B_{62.5\%} < Y \leq B_{37.5\%}$
3	NA–WB	Wysoka asynchroniczność	$X \leq A_{62.5\%}$	$Y > B_{37.5\%}$
4	ŚA–NB	Umiarkowana asynchroniczność	$A_{62.5\%} < X \leq A_{37.5\%}$	$Y \leq B_{62.5\%}$
5	ŚA–ŚB	Synchroniczność	$A_{62.5\%} < X \leq A_{37.5\%}$	$B_{62.5\%} < Y \leq B_{37.5\%}$
6	ŚA–WB	Umiarkowana asynchroniczność	$A_{62.5\%} < X \leq A_{37.5\%}$	$Y > B_{37.5\%}$
7	WA–NB	Wysoka asynchroniczność	$X > A_{37.5\%}$	$Y \leq B_{62.5\%}$
8	WA–ŚB	Umiarkowana asynchroniczność	$X > A_{37.5\%}$	$B_{62.5\%} < Y \leq B_{37.5\%}$
9	WA–WB	Synchroniczność	$X > A_{37.5\%}$	$Y > B_{37.5\%}$

X = wartości współrzędnych x wygenerowanych punktów, Y = wartości współrzędnych y wygenerowanych punktów, $A_{62,5\%}$ / $B_{62,5\%}$ = wartość zmiennej A / B o prawdopodobieństwie przekroczenia 62,5%, $A_{37,5\%}$ / $B_{37,5\%}$ = wartość zmiennej A / B o prawdopodobieństwie przekroczenia 37,5%, N = "niskie", Ś = "średnio", and W = "wysoko", A / B = analizowane zmienne.

W opracowaniu matematyczno-statystycznym danych źródłowych użyto programów Excel [Microsoft] oraz RStudio [Posit Software, PBC], będącego zintegrowanym środowiskiem programistycznym dla języka R. W toku prac wykorzystano przede wszystkim następujące pakiety: *fitdistrplus*, *copula*, *VineCopula*, *climate* (Czernecki i in. 2020), Machisplin (Brown 2020). W przygotowaniu wizualizacji elementów metodyki i wyników wykorzystano programy QGIS, ArcMap 10.8.2 [ESRI], ArcGIS Pro [ESRI] oraz Publisher [Microsoft].

Przykład obliczenia synchroniczności

Zdarzenie synchroniczne to takie, w którym wartość obydwu badanych zmiennych A i B znajduje się w tym samym przedziale prawdopodobieństwa, czyli są to relacje typu „nisko-nisko", „średnio-średnio", „wysoko-wysoko". Pozostałe typy relacji należy zaliczyć do sytuacji asynchronicznych. W celu lepszego zobrazowania tego zagadnienia przyjmujemy poniższe założenia:

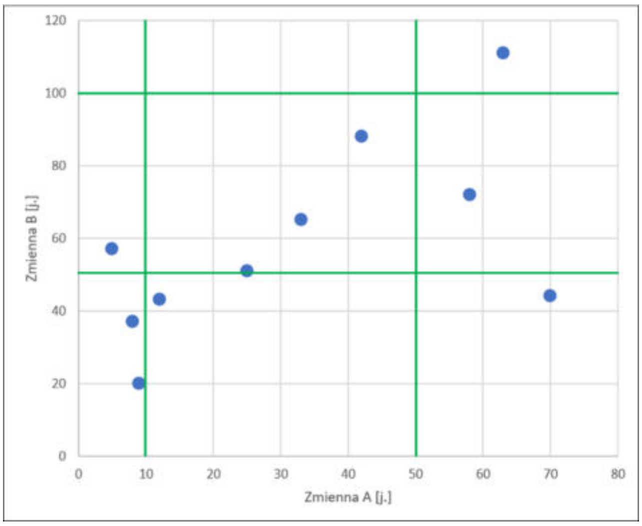
- *dla zmiennej A:*
    - *wartość o prawdopodobieństwie przekroczenia 62,5% wynosi 10 jedn.*
    - *wartość o prawdopodobieństwie przekroczenia 37,5% wynosi 50 jedn.*
- *dla zmiennej B:*
    - *wartość o prawdopodobieństwie przekroczenia 62,5% wynosi 50 jedn.*
    - *wartość o prawdopodobieństwie przekroczenia 37,5% wynosi 100 jedn.*

Zakładamy także, że ciągi danych dla zmiennych A i B przyjmowały konkretne wartości (Tab. 3), które wpisują się w przedziały wyznaczone poprzez wartości o prawdopodobieństwie przekroczenia 62,5% i 37,5% (Tab. 2).

Hipotetyczne wartości zmiennych A i B (Tab. 3) przedstawiono na wykresie z zaznaczonymi sektorami wyznaczającymi sytuacje synchroniczne i asynchroniczne (Ryc. 5). Zaprezentowany przykład nie ma charakteru probabilistycznego, ponieważ ujęte wartości dotyczą jedynie hipotetycznych wartości historycznych zmiennych A i B. Przyjmiemy założenie, że, stosując rozkład łączny tych zmiennych i stworzoną dla nich kopulę, stosunek wygenerowanych losowo punktów w poszczególnych sektorach będzie identyczny jak w przypadku wartości historycznych. W takim przypadku możemy obliczyć synchroniczność i asynchroniczność zmiennych A i B. W tym przykładzie synchroniczność wyniosłaby dokładnie 60%, a asynchroniczność 40% (asynchroniczność wysoka to 10%, asynchroniczność umiarkowana to 30%). Oznaczałoby to, że prawdopodobieństwo wystąpienia synchronicznych sytuacji w relacji zmiennych A i B wynosi 60%. Jeśli zmienne A i B dotyczyłyby wartości średniorocznych, to można by przyjąć, że takie zdarzenia występują średnio 3 razy na 5 lat.

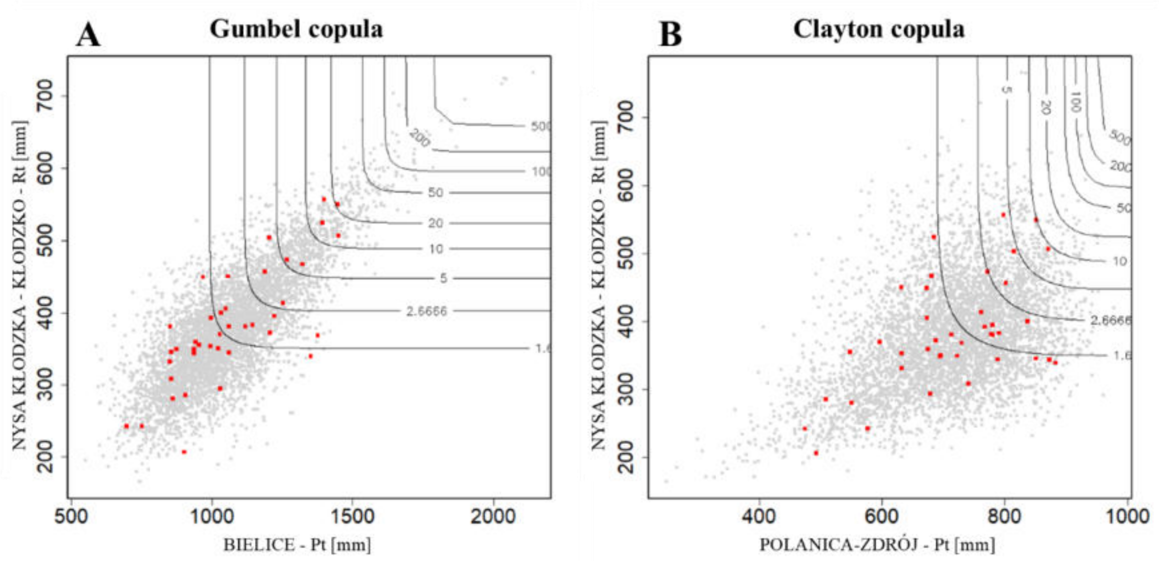
Tab. 3 Hipotetyczne wartości zmiennych A i B i ich przypisanie do sektora oraz typu relacji (por. Tab. 2)

L.p.	Zmienna A	Zmienna B	Sektor	Typ relacji
1	42	88	ŚA-ŚB	synchroniczność
2	12	43	ŚA-NB	umiarkowana asynchroniczność
3	63	111	WA-WB	synchroniczność
4	5	57	NA-ŚB	umiarkowana asynchroniczność
5	58	72	WA-ŚB	umiarkowana asynchroniczność
6	8	37	NA-NB	synchroniczność
7	33	65	ŚA-ŚB	synchroniczność
8	9	20	NA-NB	synchroniczność
9	70	44	WA-NB	wysoka asynchroniczność
10	25	51	ŚA-ŚB	synchroniczność

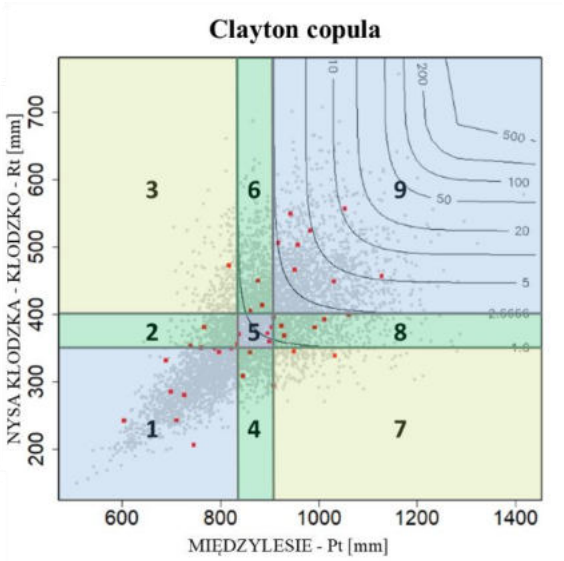


Ryc. 5 Hipotetyczne wartości zmiennych A i B (Tab. 3) naniesione na układ współrzędnych (niebieskie punkty) wraz z zaznaczonymi wartościami o prawdopodobieństwie przekroczenia 62,5% i 37,5% (zielone linie).

Przykładowe wykresy wartości empirycznych i wygenerowanych na podstawie rozkładu łącznego dla rzeczywistych danych przedstawiają Ryc. 6 i Ryc. 7.



Ryc. 6 Przykładowe wykresy dla wygenerowanych (szare punkty) i empirycznych (czerwone punkty) wartości rocznych sum opadów oraz odpływu całkowitego (Perz i in. 2021)



Ryc. 7 Przykładowy wykres dla wygenerowanych (szare punkty) i empirycznych (czerwone punkty) wartości zmiennych z zaznaczonymi sektorami synchroniczności (1, 5, 9) i asynchroniczności (pozostałe) (por. Tab. 2, Ryc. 5) (Perz i in. 2021)

5 Zarys treści artykułów

Załączone publikacje dotyczą problematyki ustalenia siły związków w ujęciu probabilistycznym i ich zróżnicowania w czasie i przestrzeni między zmiennymi hydrologicznymi, meteorologicznymi oraz ekonomicznymi w zlewni górnej Nysy Kłodzkiej. Poniżej przedstawiono główne cele badawcze poszczególnych artykułów, zastosowane w analizie dane oraz najważniejsze wnioski płynące z uzyskanych wyników. Streszczenia te nie przedstawiają wszystkich założeń, wyników i wniosków, mają jedynie na celu uwypuklenie najważniejszych cech badań i najistotniejszych rezultatów.

Artykuł nr 1

Celem pierwszego badania (Perz i in. 2021) jest wypełnienie zidentyfikowanej luki badawczej, polegającej na stosunkowo niewielkiej liczbie prac poświęconych kształtowaniu się elementów bilansu wodnego i zasobów wodnych w zlewni górnej Nysy Kłodzkiej. Jak wskazano we wprowadzeniu, większość badań związanych z hydrologią tego obszaru skupia się bowiem na wezbraniach historycznych i powodziach ekstremalnych oraz budowie modeli teoretycznych dla obliczeń związanych z wezbraniami.

W pracy zbadano związki pomiędzy rocznymi sumami opadów atmosferycznych (rejestrowanymi punktowo – w posterunkach opadowych) a odpływem całkowitym z danej zlewni. Przeanalizowano sytuację zarówno w zlewniach cząstkowych obszaru (np. odpływ ze zlewni Białej Lądeckiej po Lądek Zdrój z sumami opadów rejestrowanymi w posterunkach opadowych w tej zlewni cząstkowej – Bielice i Nowy Gierałtów), jak i całej zlewni górnej Nysy Kłodzkiej zamkniętej wodowskazem Kłodzko. Ten drugi wariant objął zatem relacje odpływu całkowitego z całego obszaru i opadów rejestrowanych we wszystkich posterunkach opadowych. Umożliwiło to interpolację wyników synchroniczności. W publikacji przedstawiono także wartości przeciętne oraz prawdopodobne rocznych sum opadów i rocznych odpływów całkowitych dla prawdopodobieństw przekroczenia 10, 1 i 0,2%, tj. średnio raz na 10, 100 i 500 lat.

Wyniki pracy wskazują, że wschodnia część obszaru (zlewnie Wilczki i Białej Lądeckiej) jest bardziej aktywna hydrologicznie, a część zachodnia (zlewnie Bystrzycy i Bystrzycy Dusznickiej) bardziej pasywna. Przez aktywność hydrologiczną rozumie się tutaj udział opadów w kształtowaniu się odpływu ze zlewni, wyrażony wartością synchroniczności opadów z odpływem z całego obszaru. Wyższe wartości synchroniczności rocznych sum opadów z odpływem całkowitym z całej zlewni po Kłodzko świadczą o dużym znaczeniu opadów atmosferycznych występujących we wschodniej części obszaru w kształtowaniu się średniorocznych warunków odpływu ze zlewni górnej Nysy Kłodzkiej jako całości.

Artykuł nr 2

Drugie badanie (Perz i in. 2022a) jest kontynuacją i rozwinięciem wątków podjętych w artykule nr 1 (Perz i in. 2021). Skupiono się w nim nie tylko na relacji opad-odpływ, ale podjęto się także analizy zróżnicowania przestrzennego rozkładu opadów atmosferycznych w obszarze badań oraz relacji pomiędzy odpływami poszczególnych zlewni. Dokonano tego poprzez ustalenie synchroniczności pomiędzy:

- rocznymi sumami opadów atmosferycznych mierzonymi w posterunkach opadowych a obszarowym (uśrednionym) opadem atmosferycznym dla całej zlewni górnej Nysy Kłodzkiej,
- rocznymi odpływami całkowitymi poszczególnych zlewni cząstkowych a rocznym odpływem całkowitym całej zlewni górnej Nysy Kłodzkiej zamkniętej wodowskazem Kłodzko,
- obszarowymi (uśrednionymi) sumami opadów atmosferycznych dla poszczególnych zlewni cząstkowych a rocznym odpływem całkowitym tych zlewni,
- obszarowymi (uśrednionymi) sumami opadów atmosferycznych dla poszczególnych zlewni cząstkowych a odpływem całkowitym całej zlewni górnej Nysy Kłodzkiej po Kłodzko.

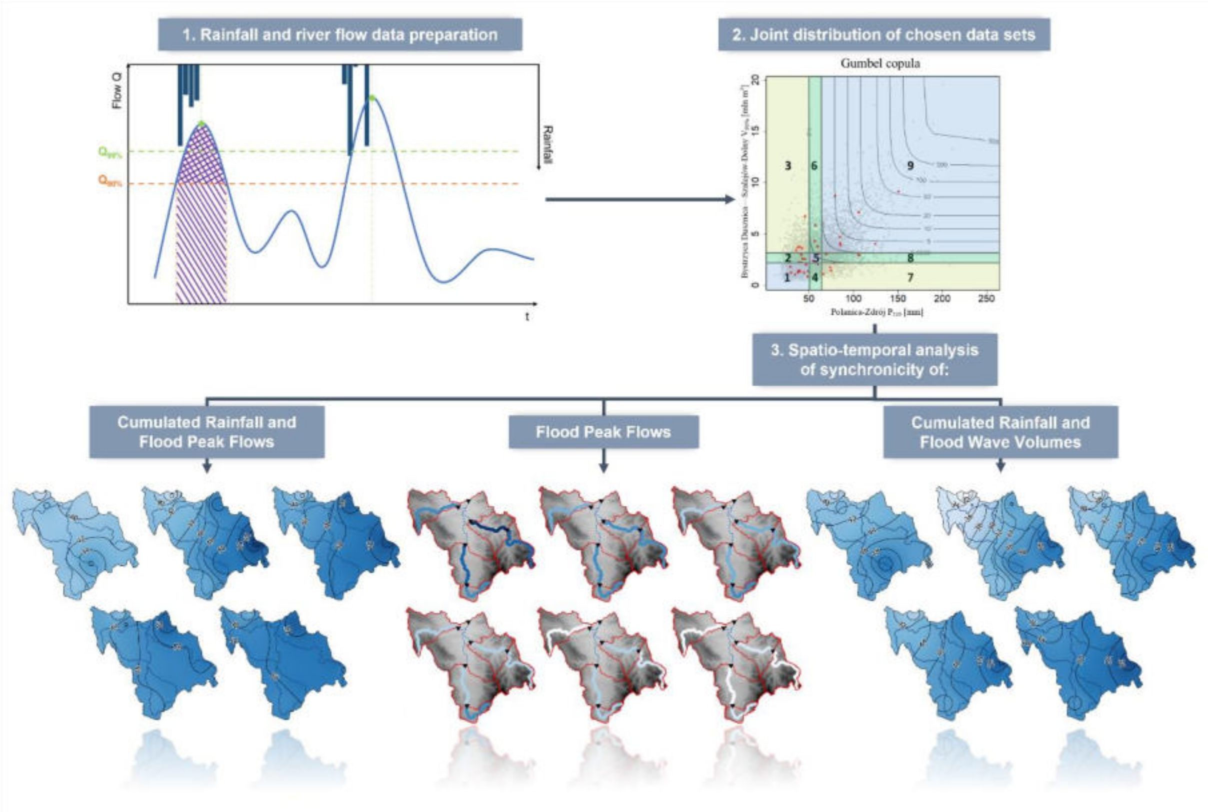
Dodatkowo, dzięki obliczeniu wartości prawdopodobnych opadów i odpływów, możliwe było ustalenie teoretycznego współczynnika odpływu dla prawdopodobieństw na poziomie 10, 1 i 0,2%, a nie tylko dla średniej sumy opadów atmosferycznych i rocznego odpływu całkowitego. Tym samym możliwe było przeanalizowanie struktury bilansu wodnego w ujęciu probabilistycznym.

Do interpolacji opadu atmosferycznego wykorzystano algorytm interpolacyjny oparty na metodach uczenia maszynowego – MICHISPLIN (Brown 2020). Bierze on pod uwagę nie tylko lokalizację posterunków, odległości między nimi i empiryczne wartości opadów atmosferycznych, ale i wysokość położenia posterunków nad poziomem morza. Tego typu modele wykorzystywane są w interpolacji opadów i uznawane są za wiarygodne (Guo i in. 2020). Interpolacji dokonano dla każdego roku z analizowanego wielolecia, uzyskując w ten sposób 40 warstw rastrowych. Następnie dla każdej zlewni cząstkowej i całego obszaru, używając narzędzia „Raster Statistics for Polygons" w QGIS, obliczono uśredniony opad obszarowy. Uzyskane wartości uszeregowano w ciągi chronologiczne i wykorzystano do dalszych analiz.

Z przeprowadzonych badań wynika m.in., że sumy opadów atmosferycznych na posterunku Międzylesie najlepiej odzwierciedlają przeciętne opady w badanej zlewni, tzn. sumy dla tego posterunku są najbardziej synchroniczne z uśrednionym opadem atmosferycznym dla całej zlewni Nysy Kłodzkiej po Kłodzko. Wyniki wskazują również na silną zależność pomiędzy odpływem ze zlewni Białej Lądeckiej a odpływem z całej zlewni Nysy Kłodzkiej po Kłodzko, a także na istotną rolę opadów w południowej i wschodniej części obszaru w kształtowaniu odpływu tego regionu. Wnioski te są spójne z wynikami przedstawionymi w artykule nr 1 (Perz i in. 2021). Zastosowanie interpolacji opadów atmosferycznych i obliczenie na ich podstawie średniego opadu obszarowego dla poszczególnych zlewni umożliwiło natomiast wyeliminowanie jednego z ograniczeń badania przedstawionego w artykule nr 1 (Perz i in. 2021) – dzięki takiemu podejściu można badać relację opad-odpływ nawet w zlewniach, w których opady atmosferyczne nie są monitorowane. W przypadku obszaru badań taką zlewnią jest zlewnia Bystrzycy, lewego dopływu Nysy Kłodzkiej.

Artykuł nr 3

Publikacja ta wpisuje się w główny nurt badań hydrologicznych w zlewni górnej Nysy Kłodzkiej, tj. w analizę meteorologicznych uwarunkowań wezbrań rzecznych i zagrożenia powodziowego (Ryc. 8).



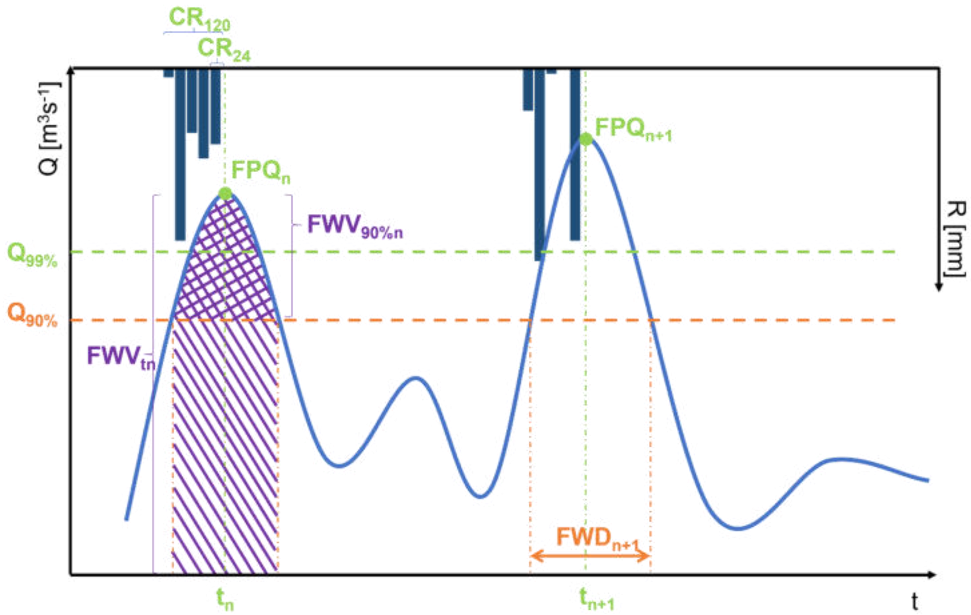
Ryc. 8 Abstrakt graficzny przygotowany dla artykułu nr 3 (Perz i in. 2022b)

Celem trzeciego badania (Perz i in. 2022b) jest identyfikacja siły relacji skumulowanych sum opadów atmosferycznych w dniach poprzedzających kulminacje letnich (V-X) fal wezbraniowych z wielkością przepływu kulminacyjnego i objętością fali wezbraniowej. Obliczenia przeprowadzono dla wezbrań odnotowanych zarówno na Nysie Kłodzkiej (wodowskazy Międzylesie, Bystrzyca Kłodzka i Kłodzko), jak i na jej dwóch największych dopływach w obszarze badań, tj. Białej Lądeckiej (wodowskazy Lądek-Zdrój i Żelazno) oraz Bystrzycy Dusznickiej (wodowskaz Szalejów Dolny). Synchroniczność obliczono dla par zmiennych opisujących:

- wybrane charakterystyki wezbrań, tj.:
  - przepływ kulminacyjny wezbrań w Kłodzku i przepływ mierzony na pozostałych wodowskazach na Nysie Kłodzkiej oraz na Białej Lądeckiej i Bystrzycy Dusznickiej w dniu wezbrania i w dniach poprzedzających,
  - przepływ kulminacyjny i objętość fali wezbraniowej dla wszystkich wodowskazów zlokalizowanych na Nysie Kłodzkiej, Białej Lądeckiej oraz Bystrzycy Dusznickiej,
- skumulowany opad atmosferyczny i wybrane charakterystyki wezbrań, tj.:
  - przepływ kulminacyjny wezbrań na wodowskazach i opady skumulowane (dla posterunków opadowych w zlewniach zamkniętych tymi wodowskazami),

- objętość fal wezbraniowych i opady skumulowane (dla posterunków opadowych w zlewniach zamkniętych tymi wodowskazami).

Kryterium wyboru fal wezbraniowych był przepływ maksymalny o wartości powyżej 99 percentyla ($Q_{99\%}$) z całego zbioru przepływów dobowych z półrocza letniego w wieloleciu 1971-2019. Dla fal wezbraniowych obliczono ich objętość w dwóch wariantach – dla szczytu fali powyżej wartości 90 percentyla przepływu ($Q_{90\%}$) oraz objętość całkowitą. Za czas trwania wezbrania przyjęto liczbę dni, w których nieprzerwanie przekroczony był poziom $Q_{90\%}$. Dla każdego z tych wezbrań obliczono sumy skumulowanych opadów dla 1, 2, 3, 4 i 5 dni przed wystąpieniem przepływu kulminacyjnego. Procedurę tę przedstawiono schematycznie na Ryc. 9.



Ryc. 9 Schemat kryterium wyboru i parametryzacji fal wezbraniowych. Oznaczenia: FPQ – przepływ kulminacyjny, FWV – objętość fali wezbraniowej, FWD – czas trwania fali wezbraniowej, CR – skumulowany opad atmosferyczny, R – opad atmosferyczny, Q – przepływ, $Q_{99\%}$ / $Q_{90\%}$ – 99 / 90 percentyl przepływu, t – czas (Perz i in. 2022b)

Badanie pozwala na sformułowanie wniosków co do relacji między istotnymi parametrami fali wezbraniowej (przepływ kulminacyjny, objętość) a opadami deszczu w zlewni górnej Nysy Kłodzkiej, a także warunków propagacji fal wezbraniowych. Do jednych z najważniejszych wniosków można zaliczyć potwierdzenie istotnego znaczenia Białej Lądeckiej w kształtowaniu się wezbrań na Nysie Kłodzkiej w Kłodzku – fala wezbraniowa na Białej Lądeckiej z większym prawdopodobieństwem wywołuje falę wezbraniową na Nysie Kłodzkiej w tych samych przedziałach prawdopodobieństwa, niż fala na Bystrzycy Dusznickiej. Warta uwagi jest także obserwacja, że warunki przepływu wód na odcinku Nysy Kłodzkiej po Międzylesie mogą odpowiadać za formowanie fal wezbraniowych w Kłodzku już na kilka dni przed ich wystąpieniem. Silniejsze relacje skumulowanych sum opadów odnotowano z przepływami kulminacyjnymi fal niż z ich objętością. Największą siłę tych powiązań zidentyfikowano dla 96-godzinnej sumy opadów mierzonych w Nowym Gierałtowie z przepływami kulminacyjnymi na Białej Lądeckiej w Żelaźnie, najmniejszą zaś – dla 24-godzinnej sumy opadów w Międzylesiu z przepływami kulminacyjnymi na Nysie Kłodzkiej w Międzylesiu.

Artykuł nr 4

Celem czwartego badania (Perz i in. 2023) jest ustalenie siły relacji skumulowanych sum opadów atmosferycznych przed wystąpieniem kulminacji fal powodziowych z wielkością potencjalnych strat powodziowych w Kłodzku. Jego problematyka ma charakter interdyscyplinarny, łącząc w jednej analizie dane hydro-meteorologiczne i ekonomiczne. Badanie odpowiada na zidentyfikowaną lukę badawczą polegającą na braku badań relacji ryzyka powodziowego (wyrażonego potencjalnymi stratami) z przestrzennym rozkładem opadów, w ujęciu probabilistycznym. Artykuł skupia się na analizie synchroniczności potencjalnych strat powodziowych w Kłodzku, obliczonych dla historycznych wezbrań letnich (V-X), i skumulowanych opadów atmosferycznych z dni poprzedzających wezbrania.

Kryterium wyboru wezbrań Nysy Kłodzkiej do dalszych analiz było przekroczenie przez kulminację fali wartości „średniej wysokiej wody" (SWW) w Kłodzku, tj. stanu 242,80 cm. Jest to wartość zbliżona do obowiązującego poziomu alarmowego (240 cm). Pozwoliło to na przyjęcie założenia, że przekroczenie tego stanu wiąże się z występowaniem strat powodziowych. Dla wytypowanych wezbrań oszacowano zasięg stref zalewu, a następnie obliczono potencjalne straty powodziowe na podstawie typu użytkowania terenu oraz przyjęte wskaźniki majątku i funkcje strat zależne od głębokości zalewu, zgodnie z obowiązującymi Mapami Zagrożenia Powodziowego i Mapami Ryzyka Powodziowego (PGW WP 2020) oraz Planami Zarządzania Ryzykiem Powodziowym (Rozporządzenie Ministra Infrastruktury, 2022). Analogicznie do metodyki przyjętej w artykule nr 3 (Perz i in. 2022b), obliczono skumulowane sumy opadów dla dni poprzedzających wytypowane wezbrania.

Wyniki badania wskazują na wysoką asynchroniczność strat powodziowych w Kłodzku i opadów z 24 godzin poprzedzających wezbranie. Oznacza to, że opady w przeddzień wystąpienia kulminacji powodzi nie decydują o maksymalnym stanie wody oraz wielkości strat. Potwierdzają to zdecydowanie wyższe wartości synchroniczności w pozostałych wariantach kumulowania opadu (od 48 do 120 godzin). Najwyższe z nich zostały odnotowane dla posterunku opadowego w Podzamku. Na podstawie uzyskanych wyników można także wnioskować, że przepływy i stany dla powodzi prawdopodobnych w Kłodzku są przeszacowane – jest to efekt uwzględnienia w obliczeniach powodzi z 1997 r., która swoimi rozmiarami znacznie przewyższa pozostałe odnotowane wezbrania.

6 Podsumowanie

W przeprowadzonych badaniach ustalono, w ujęciu probabilistycznym, związki i ich zróżnicowanie w czasie i przestrzeni między zmiennymi hydrologicznymi, meteorologicznymi oraz ekonomicznymi w zlewni górnej Nysy Kłodzkiej. Skupiono się zarówno na relacjach opadów atmosferycznych i odpływów rzecznych w ujęciu średniorocznym, jak i na związkach opadów atmosferycznych, przepływów, parametrów fal wezbraniowych i strat powodziowych w kontekście zagrożenia i ryzyka powodziowego. W pracy zastosowano metodykę opartą na kopulach, umożliwiających stworzenie rozkładu łącznego dla ciągów danych o różnych rozkładach marginalnych. Coraz częściej znajdują one zastosowanie w naukach geograficznych. Łącznie obliczono synchroniczność dla 333 par ciągów danych, z czego 232 wyniki zaprezentowano w artykule nr 3 (Perz i in. 2022b).

Uzyskane rezultaty wskazują na większą aktywność hydrologiczną wschodniej części zlewni i pasywność części zachodniej. Zarówno opady atmosferyczne występujące w zlewniach Wilczki i Białej Lądeckiej, jak i odpływy rzeczne z tych zlewni wykazują większą synchroniczność z odpływem rzecznym mierzonym dla całej zlewni po Kłodzko niż opady i odpływy ze zlewni Bystrzycy i Bystrzycy Dusznickiej. Potwierdzają to wartości współczynnika odpływu, które są wyższe dla prawej części zlewni. Można zatem wnioskować, że prawe dopływy Nysy Kłodzkiej mają szczególne znaczenie dla kształtowania średniorocznych warunków odpływu ze zlewni górnej Nysy Kłodzkiej jako całości.

Wyniki badań relacji przepływów kulminacyjnych Nysy Kłodzkiej w Kłodzku z przepływami na pozostałych wodowskazach wskazują, że wezbrania w Kłodzku mogą być efektem budowania się fali na odcinku po Międzylesie już na kilka dni przed ich wystąpieniem. Uzyskane rezultaty wskazują także na szybkie przemieszczanie się fal wezbraniowych na górnej Nysie Kłodzkiej i jej największych dopływach. Z badania relacji przepływów kulminacyjnych z objętością fal wynika z kolei, że fale wezbraniowe ulegają transformacji w trakcie przemieszczania się – synchroniczność tych zmiennych rośnie wzdłuż biegu Nysy Kłodzkiej i Białej Lądeckiej. Najsilniejsze związki parametrów wezbrań w Kłodzku z opadami skumulowanymi zidentyfikowano dla wschodniej części zlewni.

W pracy powiązano także zmienne hydro-meteorologiczne i ekonomiczne w analizie ryzyka powodziowego. Oszacowane zasięgi zalania oraz potencjalne straty dla powodzi historycznych potwierdzają istotne narażenie Kłodzka na powodzie i jego dużą podatność na straty z nimi związane. Zmierzona siła relacji skumulowanych opadów atmosferycznych i strat powodziowych wskazuje na brak powodziogennego charakteru opadów występujących tuż przed kulminacją fali – za znaczące powodzie w Kłodzku odpowiedzialne są opady wielodniowe, tj. występujące już na 4-5 dni przed szczytem fali. Najsilniejszy związek w kategoriach synchroniczności z potencjalnymi stratami powodziowymi w Kłodzku odnotowano dla opadów atmosferycznych w Podzamku.

Podsumowując, wyniki badań wskazują na skomplikowany charakter relacji zmiennych hydro-meteorologicznych oraz zagadnień związanych z zagrożeniem i ryzykiem powodziowym na obszarze zlewni górnej Nysy Kłodzkiej po wodowskaz Kłodzko. Należy zwrócić uwagę na szczególną rolę wschodniej części analizowanego obszaru zarówno w kształtowaniu się odpływu z całej zlewni zamkniętej wodowskazem Kłodzko, jak i w poszukiwaniu przyczyn zagrożenia powodziowego Kłodzka.

Przeprowadzone badania są istotne z poznawczego punktu widzenia, ponieważ pomagają lepiej zrozumieć kształtowanie się oraz przebieg zjawisk i procesów hydro-meteorologicznych w zlewni górnej Nysy Kłodzkiej. Otrzymane rezultaty rzucają nowe światło zarówno na przestrzenny rozkład opadów atmosferycznych i odpływów, jak i ich znaczenie w kontekście kształtowania się bilansu wodnego regionu oraz reżimu hydrologicznego, zwłaszcza w fazie wezbrań.

Artykuły składające się na rozprawę są spójne metodycznie – wszystkie relacje analizowano w kontekście synchroniczności, obliczonej na podstawie kopul. Uzyskane rezultaty pozwalają wyciągnąć wniosek o ich przydatności w prowadzeniu badań relacji zmiennych opisujących środowisko geograficzne. Wypracowana metodyka może zostać zastosowana w badaniu innych regionów Polski i świata. Co więcej, udowodniono także możliwość użycia jej w badaniach interdyscyplinarnych, łączących z sobie dane hydro-meteorologiczne i ekonomiczne w ocenie ryzyka powodziowego. Ujęcie probabilistyczne badanych relacji umożliwiło z kolei analizę sytuacji prawdopodobnych, a nie tylko empirycznych. Wykazano również, że wykorzystanie obszarowych sum opadów umożliwia badanie relacji opad-odpływ nawet w zlewniach nieobjętych monitoringiem opadów atmosferycznych.

Uzyskane rezultaty mogą mieć również znaczenie aplikacyjne, ponieważ dotyczą bezpośrednio zagadnień związanych z gospodarką wodną, w tym z zasobami wodnymi i narażeniem na powódź. W dobie postępującej zmiany klimatu i jej licznych konsekwencji dla obiegu wody, racjonalne wykorzystanie zasobów wodnych, ich właściwie rozpoznanie i ochrona nabierają kluczowego znaczenia dla zachowania możliwości rozwoju społeczno-gospodarczego. Jednakże woda to nie tylko zasób, ale i zagrożenie – na terenach górskich najczęściej związane z jej okresowym nadmiarem, czyli powodziami. Dlatego badania relacji opadów atmosferycznych z wezbraniami mają także charakter praktyczny, a ich wyniki mogą być wykorzystane np. w trakcie procesu planistycznego związanego z ochroną przeciwpowodziową czy tworzenia systemów wczesnego ostrzegania.

W ocenie autora, uzyskane rezultaty pozwalają uznać, że szczegółowe cele badawcze, a tym samym i cel główny, zostały zrealizowane. Część zidentyfikowanych związków bez wątpienia wymaga dalszych badań – do takich należy np. zaskakująca swoją siłą relacja pomiędzy opadami atmosferycznymi w Podzamku a potencjalnymi stratami powodziowymi w Kłodzku (artykuł nr 4). Ponadto w każdym z artykułów przedstawiono możliwe dalsze kierunki badawcze, zarówno pod względem rozwoju metodyki (np. poprzez wypracowanie ilościowej metody oceny niepewności wyników synchroniczności lub wykorzystanie kopul wielowymiarowych), jak i dalszego badania relacji zmiennych hydro-meteorologicznych w obrębie zlewni górnej Nysy Kłodzkiej (np. w kontekście występowania suszy i niżówek czy powodzi roztopowych). Ciekawym zagadnieniem może być także ocena prawidłowości wyznaczonych przepływów i stanów prawdopodobnych pod kątem ich możliwego przeszacowania lub niedoszacowania w kontekście planowania ochrony przeciwpowodziowej.

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Article

Probabilistic Approach to Precipitation-Runoff Relation in a Mountain Catchment: A Case Study of the Kłodzka Valley in Poland

Adam Perz *, **Leszek Sobkowiak** and **Dariusz Wrzesiński**

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Abstract: On the basis of daily precipitation and discharges recorded in 1974–2013 relations between precipitation and runoff in the Kłodzka Valley (KV) in south-western Poland were analyzed. The degree of synchronicity between them was determined using the bivariate Archimedean copulas. This study aims at identifying and then describe in a probabilistic way the precipitation and runoff relations in the area playing an important role in the formation of water resources, but also particularly exposed to flooding. It was found that isolines of the synchronous occurrence of precipitation and total runoff in the Nysa Kłodzka catchment controlled by gauge Kłodzko had a zonal distribution, with the synchronicity values decreasing from south-east to north-west of the study area. This proves that its eastern part is more hydrologically active, compared to the western part, and as such it determines the amount of water resources of the study area. The decrease in synchronicity is influenced by the type and spatial distribution of precipitation, the structure of water supply, and the geological structure of the study area. Moreover, probabilistic methods applied in this research differ from those used in previous research on the hydrology of KV, as we propose using the copula functions. The method presented can be used to evaluate the availability of water resources in areas playing a key role in their formation on different scales.

Keywords: precipitation; runoff; Archimedean copula; synchronicity; river regime; rainfall-runoff modeling; central Europe

Citation: Perz, A.; Sobkowiak, L.; Wrzesiński, D. Probabilistic Approach to Precipitation-Runoff Relation in a Mountain Catchment: A Case Study of the Kłodzka Valley in Poland. *Water* **2021**, *13*, 1229. https://doi.org/10.3390/w13091229

Academic Editor: Koichiro Kuraji

Received: 15 April 2021
Accepted: 26 April 2021
Published: 28 April 2021

1. Introduction

The hydrological cycle has many interconnected components, with runoff connecting precipitation to bodies of water [1]. A wide range of rainfall-runoff models are currently used by researchers and practitioners; however, the applications of these models are highly dependent on the purposes for which the modeling is made [2]. There is much rainfall-runoff modelling that is carried out purely for research purposes as a means of formalizing knowledge about hydrological systems. The demonstration of such understanding is an important way to develop an area of science. However, the ultimate aim of prediction using models must be to improve decision making about a hydrological problem, whether that be in water resource planning, flood protection, mitigation of contamination, licensing of abstractions, or other areas [3]. While there are many examples of studies focusing primarily on the hydrological consequences of the assumed rainfall [4–8], the researches have rarely analyzed the precipitation-runoff relationship in terms of the water resource forming and the river regime types in the given area.

The Kłodzka Valley (hereinafter referred to as KV) in south-western Poland is an area particularly vulnerable to catastrophic floods, in particular triggered by excessive rainfall during the summer months. It is located in the Sudetes Mountains, which along with the Sudeten foreland is the second richest in water resources of the regions of Poland, after the Carpathians [9]. KV is a part of the Odra River basin, which belongs to the Baltic Sea drainage basin. Extreme rainfall, most often leading to floods in the upper and middle Odra basin, is usually associated with low pressure centers (of frontal origin) moving over Poland from southern Europe along the Vb route according to Van Bebber's classification. These rainfall events are long-lasting, even up to several days [10]. Moreover, apart from the weather, the morphological conditions of the area (altitude, exposure, terrain, etc.) usually play an important role in shaping the distribution of the fields of intense precipitation. Particularly important is the orographic forcing of humid air masses, flowing from the northern sector, on the orographic barrier, which in the Odra River basin are formed by the Sudetes. Hence, the highest sums of one- or several-day rainfall with high intensity occur in the mountains. Thus, the amount of water discharged from mountain catchments has the most important and largest share in the formation of floods on the Odra River [11].

There have been numerous case studies focusing on the extreme floods recorded in KV. They were devoted to the estimation of the precipitation volume causing summer floods [11], the history of summer floods during the last centuries [12], or the role of torrential rains and floods in modeling the relief of KV [13]. Besides these studies based on the recorded datasets, there were also theoretical models constructed for the KV rivers [14–17]. Among the scientific contributions of these papers, the discovery of a meaningful level of differences between the daily maximum and mean design discharges and between the rate of change of flood magnitude can be mentioned [14]. Important from the practitioners' point of view, in [15] a new system for computing the multi-model ensemble predictions of water levels (called HydroProg) is proposed, applied in the process of real-time modeling and forecasting of river flow in the upper Nysa Kłodzka catchment.

While the aforementioned studies focus on the analysis of floods in KV or on the overall catchment response to the occurrence of precipitation, there are few analyses related to the total water abundance in that area. Olichwer [18] studied the long-term variability of water resources in the Kłodzko region through the characteristics of the total and groundwater runoff. In analyzing the variability of the total and groundwater runoff, decreasing long-term trends in the total and groundwater runoff can be observed. It is primarily affected by very noticeable declining trends during the summer period, which is related to both the total and groundwater runoff. Perz [19] identified the characteristics of the flow regime of the rivers in KV in terms of the runoff, the structure, and the spatio-temporal variabilities. He determined that the runoff conditions in the analyzed sub-catchments were different and found that the rivers in KV had different regime characteristics, and that there were significant differences in the total runoff, from 375 mm in Kłodzko to above 700 mm in the Wilczka River. The differences were also concluded in terms of the groundwater runoff and its contribution to the total runoff, which ranged between 31% and 53%.

As can be seen from the above review, numerous researchers analyzed relations between extreme precipitation and runoff in KV. However, there is a lack of research on the water resources and relations between average values of precipitation and runoff in that area. This study aims at filling this research gap by identifying and then describing elements of the water balance, and more specifically precipitation and runoff relations in the area playing an important role in formation of water resources, but also particularly exposed to flooding. Moreover, probabilistic methods applied in this research differ from those used in previous research on hydrology of KV, as we propose to use the copula function, which has been widely recognized in studies on the synchronous occurrence of hydrological and meteorological phenomena in a catchment. Recently the bivariate copulas have been successfully applied to analyze dependencies between precipitation and runoff in the Upper Huai River Basin in China [20], the maximum runoff synchronicity and its spatial differentiation in the Warta River catchment in Poland [21], and the maximum and mean flow synchronicity in the Upper Indus River Basin in Pakistan [22].

2. Study Area and Methods

2.1. Study Area

KV is located in the south-western part of Poland, and in this paper it is understood as an area drained by the upper section of the Nysa Kłodzka River and its tributaries to gauge Kłodzko (Figure 1). According to the physical-geographical regionalization of Poland by Kondracki [23] KV belongs to the sub-province Sudetes with the Sudetes Foreland, and to two macro-regions: The Central Sudetes and the Eastern Sudetes. That area includes the following meso-regions: The Upper Nysa Trench, the Śnieżnik Massif, the Złote Mountains, the Bardzkie Mountains, the Bystrzyckie Mountains, the Orlickie Mountains, the Table Mountains, the Kłodzka Valley (KV), and the Ścinawka Depression [23,24].

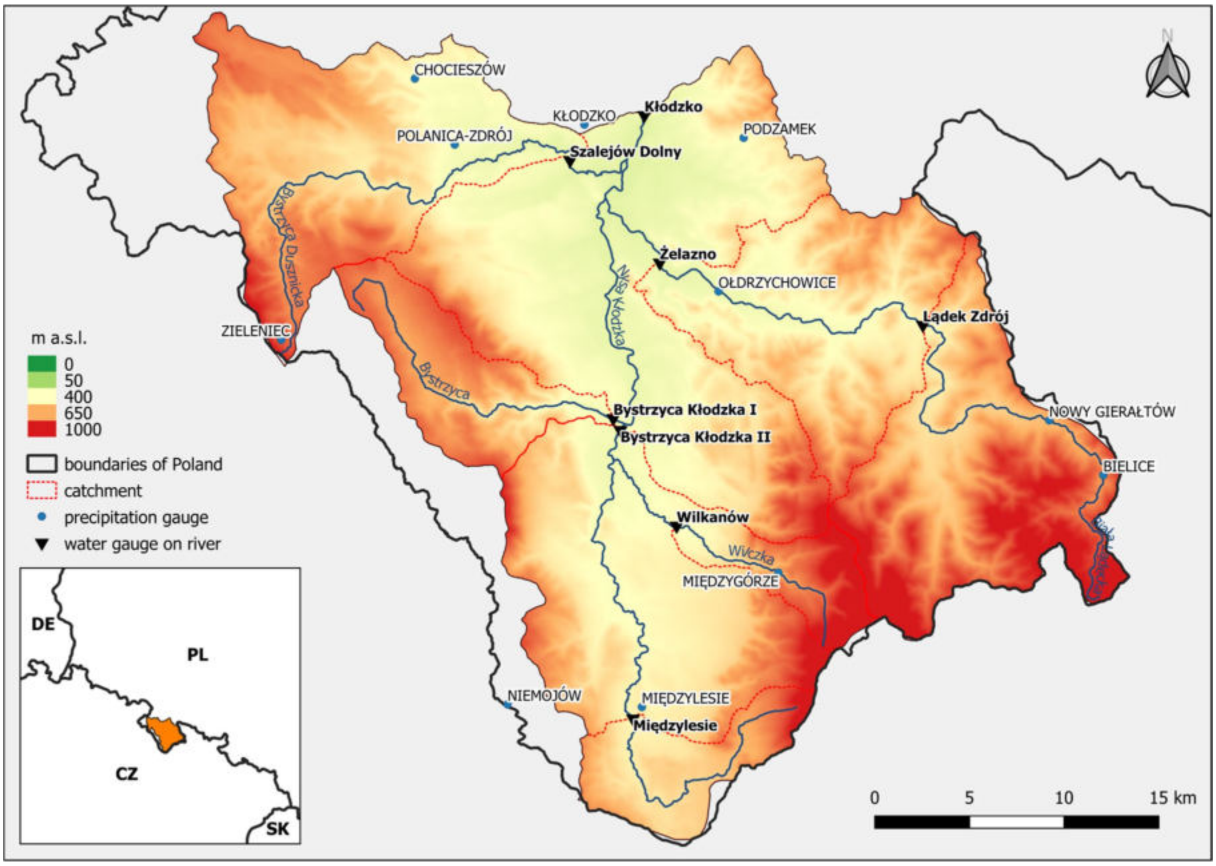

Figure 1. Study area and its geographical position in Poland.

According to [23,24], KV is a tectonic ditch running longitudinally and dividing the Sudetes into the central and eastern parts. In the western part it is bordered by the Bystrzyckie Mountains, and in the eastern part by the Śnieżnik Massif, the Złote Mountains, and the Bardzkie Mountains [23]. KV does not have a clearly defined northern border, with the Lower Ścinawka River and the Noworudzkie Lowering being its extensions [23]. The study area is characterized by relatively large differences in altitude: The Three-Seas Peak is 1145 m a.s.l., while the lowest part of the Kłodzko town is situated about 280 m a.s.l. (Figure 1). In terms of geology, KV is characterized by little variability [13]; the pre-Cambrian metamorphic rocks and sedimentary rocks of the Cretaceous period are dominant. On the other hand, KV is diversified in terms of structure and texture, as well as rock resistance to erosion and weathering processes [13]. The study area has an undulating and hilly, mid-mountain relief, with river valleys characterized by a distinct morphological expression and a different degree of development of the channel system as its important element [13]. Besides river sediments in the valleys, there are remnants of moraine covers and stagnant clays, resulting from the double overlapping by the continental glacier through the passes of the Bardzkie Mountains [23]. The bottom of the valley is partially covered with loess, on which fertile soils have developed. This was of key importance to the development of agriculture, which on turn resulted in significant deforestation of that area [23].

The 182-km long Nysa Kłodzka is the left tributary of the Odra (Oder) River, the second-longest river of Poland. The Nysa Kłodzka is the main river of KV. It has its source in the Śnieżnik Massif, on the slope of the Three-Seas Peak, at an altitude of over 1000 m a.s.l. Initially, the river runs along the Upper Nysa Ditch, which is its natural drainage channel [25]. Then it flows into Kłodzka Valley, where it retains its mountain character until it flows out of the Bardo Mountains. Then, it begins to meander and becomes a lowland river. Its main tributaries within the analyzed area are: The Wilczka (18.2 km), Bystrzyca (25.5 km), Biała Lądecka (52.7 km), and Bystrzyca Dusznicka (33 km) rivers. Their mountainous character along with the topography and geology of their watersheds make these watercourses very prone to floods triggered by sudden or prolonged rainfalls and thaws. For example, the summer flood of July 1997, known as the "millennium flood", caused huge material losses not only in the Kłodzko region, but also in cities along the Oder River, including Wrocław, killing several dozen people in total. The amount of flood losses is also significantly increased by the concentration of assets in the form of buildings and infrastructure in the river valleys and along the watercourses. For example, the subsoil in the Bystrzyca River watershed is largely made of low-thickness loams [16], which are characterized by a medium water permeability. Therefore, they contribute to increasing surface runoff and faster formation of floods on watercourses.

In terms of climate the upper part of the Nysa Kłodzka catchment is classified as the so-called Kłodzko climatic region of the Sudetes climate district [26]. The lowest temperatures are recorded in the Bystrzyckie Mountains (annual average 4.9 °C), while the highest in the foreland of the Opawskie Mountains (above 8 °C) [26]. The annual precipitation in the analyzed area is varied spatially. In general, higher values are recorded in mountains, that is in the south, west, and east of that area, especially in the watershed of the Bystrzyca Dusznicka and Wilczka rivers, and the upper Biała Lądecka River (Figure 1). On the other hand, the precipitation decreases in the central and northern parts of the area, that is within the lower parts of KV (Figure 1). Among the analyzed rainfall stations, the highest annual precipitation is recorded in Zieleniec (1279 mm), while the lowest is in Kłodzko (577 mm) (Table 1). There are noticeable variations in precipitation on the multi-annual and monthly bases. According to the Köppen–Geiger classification of climates [27] the study area lies within the zone of cold climate with relatively cold winters and warm summers (Dfb). Wrzesiński [28,29] classified the river regime of the study area as nival-pluvial and pluvial-nival. Perz [19] based on the data from 1971–2015 classified rivers of KV into two of five types of regimes: Type 2-nival moderately developed, characteristic of the upper section of the Nysa Kłodzka above gauge Międzylesie and its left-bank tributaries-the Bystrzyca and the Bystrzyca Dusznicka rivers, and type 4-nival-pluvial regime, characteristic of the Nysa Kłodzka River below gauge Międzylesie, as well as the Biała Lądecka and Wilczka rivers (Figure 1, Table 2).

2.2. Data Sets

The study is based on the values of daily precipitation and runoff collected in KV in the multi-year period 1974–2013. Precipitation data were recorded at 11 rain gauge stations (Figure 1, Table 1), while runoff data at eight water gauge stations, three of which are located on the Nysa Kłodzka River, and five on its tributaries—the Wilczka, Bystrzyca, Biała Lądecka and Bystrzyca Dusznicka rivers (Figure 1, Table 2).

In has to be noted that, in case of the Bystrzyca River catchment, the average and probable values were calculated, but they were not presented in the results, because of the lack of rain gauge in that catchment, towards which the synchronicity could be analyzed. Additionally, for the purpose of interpolation of the average and probable values of precipitation, data from the Niemojów rain gauge station were applied; however, they were not included in the synchronicity analysis because of location of that gauge beyond the analyzed area. Interpolation of the precipitation values was conducted by means of the Inverse Distance Weighting (IDW) interpolation method.

Table 1. Basic characteristics of analyzed rain gauge stations.

Rain Gauge Station	Coordinates		Altitude (m a.s.l.)	Annual Precipitation (mm)
	Latitude	Longitude		
Bielice	50°16′ N	17°00′ E	695	935.9
Chocieszów	50°27′ N	16°29′ E	405	765.2
Kłodzko	50°26′ N	16°36′ E	356	577.2
Międzygórze	50°13′ N	16°46′ E	585	985.4
Międzylesie	50°09′ N	16°40′ E	450	860.3
Niemojów	50°09′ N	16°34′ E	570	1005.8
Nowy Gierałtów	50°18′ N	16°57′ E	635	900.4
Ołdrzychowice	50°21′ N	16°43′ E	340	747.5
Podzamek	50°25′ N	16°43′ E	400	765.3
Polanica-Zdrój	50°25′ N	16°31′ E	390	873.3
Zieleniec	50°19′ N	16°23′ E	845	1277.8

Table 2. Basic characteristics of analyzed river gauges.

River	Gauge	Coordinates		Altitude (m a.s.l.)	Catchment Area (km^2)	Runoff Depth (mm)	River Regime Type [1]
		Latitude	Longitude				
Nysa Kłodzka	Międzylesie	50°09′ N	16°39′ E	426	49.7	444	2
	Bystrzyca Kłodzka II	50°17′ N	16°39′ E	338	260.0	481	4
	Kłodzko	50°26′ N	16°39′ E	281	1084.0	375	4
Wilczka	Wilkanów	50°14′ N	16°41′ E	363	35.1	715	2
Bystrzyca	Bystrzyca Kłodzka I	50°17′ N	16°39′ E	340	64.0	484	2
Biała Lądecka	Lądek Zdrój	50°20′ N	16°52′ E	421	166.0	649	4
	Żelazno	50°22′ N	16°40′ E	317	305.0	508	4
Bystrzyca Dusznicka	Szalejów Dolny	50°25′ N	16°34′ E	305	175.0	388	2

[1] Types of river regime: 2—nival moderately developed; 4—nival-pluvial (Source: [19,28,29] modified).

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

2.3. Methods

The copula functions have been applied to analyze the synchronous and asynchronous occurrence of precipitation and runoff in river catchments situated in KV. In this study the bivariate Archimedean copulas were used. The concept of copula was introduced by Sklar [30], who defined copula as a joint distribution function of standard uniform random variables. Results of many researchers proved that copulas can be a powerful tool for modeling and sampling multivariate, nonlinearly interrelated hydro-meteorological data [31].

First, the best matching statistical distributions (from Weibull, Gamma, Gumbel, and log-normal) were selected for the analyzed data series. The maximum likelihood method was used to estimate values of distribution parameters. The goodness of fit of a given distribution in the data series was checked by means of the Akaike information criterion (AIC) [32]:

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

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

$$\text{AIC} = -2\log\,(\text{maximum likelihood for model}) + 2\,(\text{no. of fitted parameters}). \tag{2}$$

The best fitted distribution type is the one that has the minimum AIC value [32].

Next, the joint distribution of Pt (mm) and Rt (mm) was constructed. It was made for data from each precipitation gauge located in a given catchment with data from a water gauge (closing this particular catchment). In other words it was made only for each pair of hydrologically connected precipitation and runoff data sets, to avoid analyzing random/accidental statistical relations between gauges without hydrological connection.

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

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

where u and v are marginal distributions, the θ, subscript of copula C, is the parameter hidden in the generating function ϕ, and ϕ is a continuous function called a generator that strictly decreases and is convex from I = [0, 1] to [0, ϕ (0)] [33].

The Archimedean copula family is often applied in hydrological studies [34], for example in flood frequency analyses. It was found that a copula-based flood frequency analysis performs better than a conventional flood frequency analysis, as joint distribution based on a copula fits the empirical joint distribution (i.e., from observed data using a plotting position formula) better than the established standard joint parametric distribution.

A large variety of copulas belongs to the Archimedean copula family and can be applied when the correlation between hydrological variables is positive or negative. The proofs of these properties have been reported by Genest and Favre [35]. For this reason, one-parameter Archimedean copulas, including the Clayton family, the Gumbel–Hougaard family, and the Frank family, were used in this study. The Gumbel–Hougaard and Clayton copula families are appropriate only for positively correlated variables, while the Frank family is appropriate for both negatively and positively correlated variables (Table 3).

Table 3. Copula function, parameter space, generating function $\phi(t)$, and functional relationship of Kendall's τθ with a copula parameter for selected single-parameter bivariate Archimedean copulas.

Copula Family	$C_\theta(u,v)$	Generator $\phi(t)$	Parameter $\theta\in$	Kendall's τ_θ
Clayton	$max\left(\left(u^{-\theta}+v^{-\theta}-1\right)^{-\frac{1}{\theta}},0\right)$	$\frac{1}{\theta}\left(t^{-\theta}-1\right)$	$[-1,\infty)\backslash\{0\}$	$\tau=\theta/(2+\theta)$
Gumbel–Hougaard	$exp\left\{-\left[(-ln\ u)^{\theta}+(-ln\ v)^{\theta}\right]^{\frac{1}{\theta}}\right\}$	$(-\ln t)^{\theta}$	$[1,\infty)$	$(\theta-1)/\theta$
Frank	$\frac{-1}{\theta}ln\left[1+\frac{(e^{-\theta u}-1)(e^{-\theta v}-1)}{e^{-\theta}-1}\right]$	$-ln\frac{e^{-\theta t}-1}{e^{-\theta}-1}$	$(-\infty,\infty)\backslash\{0\}$	$1+4[D_1(\theta)-1]/\theta$

$$D_k(x) = \frac{k}{x^k}\int_0^x \frac{t^k}{e^t-1}dt. \tag{4}$$

where $Dk_{(x)}$ is Debye function, for any positive integer k (order of the function).

The best-fitted joint distribution was selected through comparison to the empirical joint distribution using the Akaike information criterion (AIC), as mentioned earlier.

For each pair of series, based on previously computed statistical distribution parameters of marginal data series, 5000 hypothetical values were randomly generated. They were used for the selection of the best-fitted copula family for a given pair of data sets and next for the forming of an appropriate copula. Based on empirical value pairs (red points in Figure 2) for particular years and computed hypothetical points (marked with gray in Figure 2), graphs with probability curves (expressed in return periods) were generated (Figure 2).

All these steps allowed calculating the degree of synchronicity (synchronous occurrence) and asynchronicity (asynchronous occurrence) of Pt and Rt. For each pair of gauges, probability curves at a level of 62.5% (once in 1.6 years), 37.5% (once in approximately 2.7 years), 20% (once in 5 years), 10% (once in 10 years), 2% (once in 50 years), 1% (once in 100 years), 0.5% (once in 200 years), and 0.2% (once in 500 years) were generated (Figures 2 and 3).

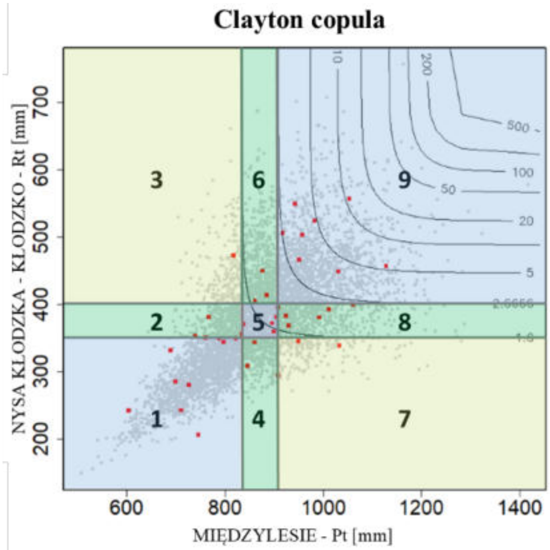

Figure 2. Example of combined accumulated curves of the probability of exceedance and the determination of sectors (1–9) with their various degrees of synchronicity or asynchronicity. Red points—empirical pairs of values; grey points—generated theoretical points based on calculated parameters of joint distribution.

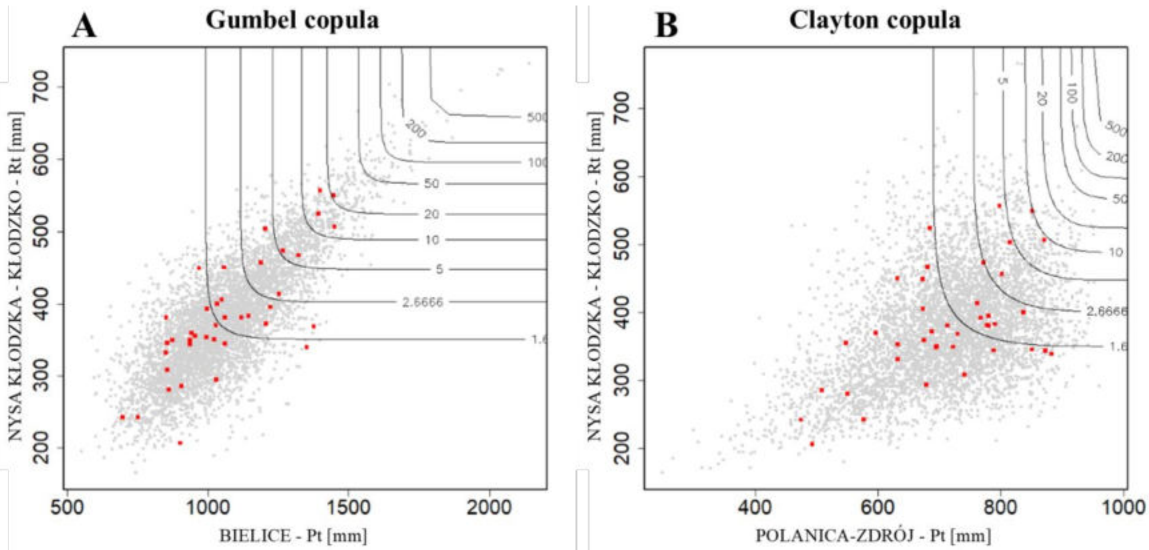

Figure 3. Examples of copula plots of gauges with: (**A**) the maximum synchronicity (gauges: Bielice–Kłodzko) and (**B**) the maximum asynchronicity (gauges: Polanica–Zdrój–Kłodzko) of the Pt and Rt in 1974–2013.

Then, the obtained data (generated value pairs) were analyzed in basis 62.5% and 37.5% probability levels [36,37]. According to these levels, nine sectors were designated. They represent different relations between probable values of Pt and Rt. Based on generated value pairs with a distribution imitating the joint distribution of values from compared gauges and their participation in particular sectors (Figure 2), three sectors with the synchronous occurrences of Pt and Rt were designated:

- Sector 1: LPt–LRt ($X \leq Pt_{62.5\%}$, $Y \leq Rt_{62.5\%}$);
- Sector 5: MPt–MRt ($Pt_{62.5\%} < X \leq Pt_{37.5\%}$, $Rt_{62.5\%} < Y \leq Rt_{37.5\%}$);
- Sector 9: HPt–HRt ($X > Pt_{37.5\%}$, $Y > Rt_{37.5\%}$);

and six sectors with the asynchronous occurrences:

- Sector 2: LPt–MRt ($X \leq Pt_{62.5\%}$, $Rt_{62.5\%} < Y \leq Rt_{37.5\%}$);
- Sector 3: LPt–HRt ($X \leq Pt_{62.5\%}$, $Y > Rt_{37.5\%}$);

- Sector 4: MPt–LRt ($Pt_{62.5\%} < X \leq Pt_{37.5\%}$, $Y \leq Rt_{62.5\%}$);
- Sector 6: MPt–HRt ($Pt_{62.5\%} < X \leq Pt_{37.5\%}$, $Y > Rt_{37.5\%}$);
- Sector 7: HPt–LRt ($X > Pt_{37.5\%}$, $Y \leq Rt_{62.5\%}$);
- Sector 8: HPt–MRt ($X > Pt_{37.5\%}$, $R_{62.5\%} < Y \leq Rt_{37.5\%}$).

where X = the values of x coordinates of generated points, Y = the values of y coordinates of generated points, $Pt_{62.5\%}$ = the value of Pt with a probability of exceedance of 62.5%, $Pt_{37.5\%}$ = the value of Pt with a probability of exceedance of 37.5%, $Rt_{62.5\%}$ = the value of Rt with a probability of exceedance of 62.5%, $Rt_{37.5\%}$ = the value of Rt with a probability of exceedance of 37.5%, L = "low", M = "medium", and H = "high".

The percent share of generated points in sectors 1, 5, and 9 allowed determination of the degree of synchronicity of Pt and Rt (i.e., between compared precipitation gauge and water gauge on a river). The asynchronicity may be divided into two types: Moderate (the percent share of points in sectors 2, 4, 6, 8—"low-medium", "medium-low", "medium-high", and "high-medium" relations) and high (the percent share of points in sectors 3 and 7—"high-low" and "low-high" relations), respectively.

In other words, the synchronous and asynchronous occurrences of Pt and Rt were determined through a calculation of threshold values of probability ranges:

- Probable values with a probability of occurrence of <62.5% were designated as LPt/LRt;
- Probable values with a probability of occurrence in a range >62.5% and <37.5% were designated as MPt/MRt;
- Probable values with a probability of occurrence > 37.5% were designated as HPt/HRt.

The sum of percent share of synchronous and asynchronous events is always 100%.

For instance, the occurrence of LPt in a given precipitation gauge is a synchronous event if in the same time unit LRt occurs in the catchment (closed by water gauge) which the precipitation gauge is located in, whereas it is the asynchronous one if MRt or HRt occurs.

If the synchronicity of Pt and Rt in a given catchment is 60%, this means that in three out of five years, the probable Pt at a given gauge is within the same probability range as the probable Rt.

In turn, the asynchronicity can be exemplified by the occurrence of high Pt in the given catchment (e.g., a "100-year precipitation", $p = 1\%$) and the occurrence of low Rt in the same catchment (e.g., at the level of exceedance probability $p = 90\%$). As in the example above, if the synchronicity is 60%, the asynchronicity is 40%, which means that statistically the asynchronous event should occur average twice for every five years.

In the Section 3, the term "synchronicity"/"asynchronicity" means the synchronous/asynchronous occurrence of Rt relative to the Pt in the described catchment. Interpolation both of the synchronicity and precipitation values was conducted by means of the IDW interpolation method.

For the mathematical and statistical processing MS Excel and RStudio software were used. QGIS and MS Publisher software was employed to visualize the obtained results.

3. Results

3.1. Probable Values of Pt and Rt

The values of the total runoff in the study area are varied (Figure 4A). They reach the highest values in the eastern part of KV, in the Wilczka (about 740 mm) and Biała Lądecka river catchments (655 mm in gauge Lądek–Zdrój and 512 mm in gauge Żelazno, respectively), while in the whole Nysa Kłodzka catchment area closed by gauge Kłodzko it is significantly lower (about 380 mm). The average precipitation has a specific spatial pattern: Its higher values are recorded in the elevated areas, that is in the western, eastern, and southern parts of KV, and the values decrease towards the north (Figure 4A). The highest average annual rainfall is recorded in the upper Bystrzyca Dusznicka catchment (about 1250 mm).

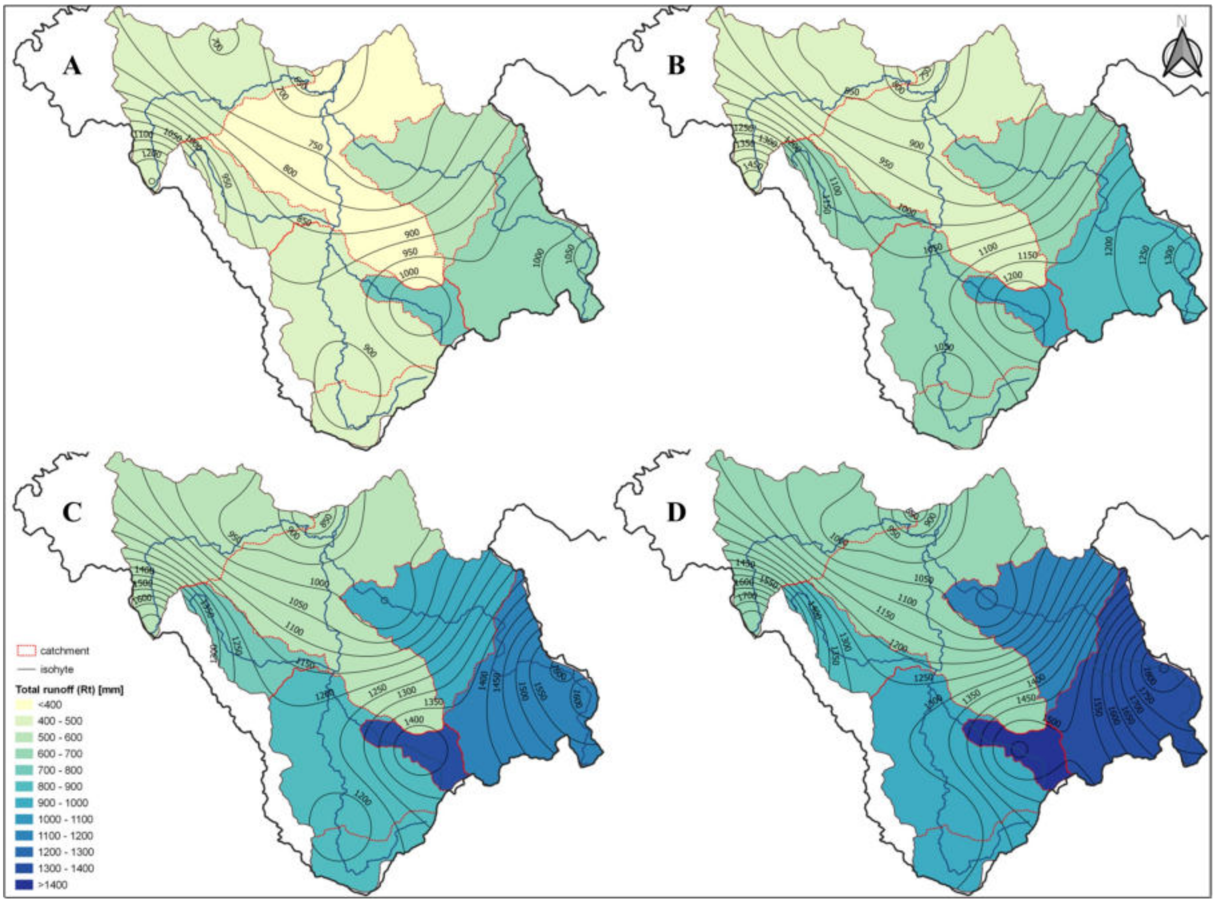

Figure 4. Precipitation and total runoff in the analyzed catchment areas of KV: (**A**) Average values for the multi-year period 1974–2013, (**B**) with an exceedance probability of 10%, (**C**) with an exceedance probability of 1%, and (**D**) with an exceedance probability of 0.2%.

In general, the spatial distribution of the annual precipitation totals with the exceedance probabilities of 10% (Figure 4B), 1% (Figure 4C), and 0.2% (Figure 4D) follows the distribution of average values of precipitation and runoff (Figure 4A). In the case of the exceedance probabilities of 10% (Figure 4B) and 1% (Figure 4C), the highest precipitation is expected at gauge Zieleniec located in the Bystrzyca Dusznicka catchment, analogically to the annual averages. However, the spatial distribution of precipitation with the exceedance probability of 0.2% is different, and the highest values of annual precipitation can be expected in the Biała Lądecka catchment (over 1850 mm).

The probable values of the annual runoff refer spatially to the annual precipitation totals. Much higher values, similar to the mean values (Figure 4A), are characteristic for the Wilczka and Biała Lądecka catchments, and the upper part of the Nysa Kłodzka River.

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

3.2. Synchronicity of Pt and Rt

The results shows different degrees of the synchronous occurrence of the river runoff with the annual precipitation recorded in the catchment (Table 4). The strongest relationship has been demonstrated between precipitation recorded in rain gauge Zieleniec and runoff in the Bystrzyca Dusznicka River sub-catchment controlled by water gauge Szalejów Dolny (65.7%), then precipitation in rain gauge Międzylesie and runoff in the Nysa Kłodzka River catchment controlled by water gauge Międzylesie (64.8%), and also precipitation in rain gauge Bielice and runoff in the Nysa Kłodzka River catchment controlled by water gauge

Kłodzko (64.4%). By contrast, the least synchronous were the precipitation totals recorded in rain gauge Polanica–Zdrój and runoff in the Nysa Kłodzka River catchment controlled by water gauge Kłodzko (49.1%), and also precipitation in rain gauge Ołdrzychowice and runoff in the Biała Lądecka River sub-catchment down to Żelazno (49.4%).

Table 4. The percent synchronicity and asynchronicity of precipitation and runoff in analyzed rain gauge stations and water gauges in KV.

Rain Gauge Station	Sectors									Syn.	Asyn.		
	1	5	9	2	4	8	6	3	7		Total	Moderate	High
Nysa Kłodzka River at gauge Międzylesie													
Międzylesie	27.7	10.2	26.9	7.2	7.5	7.4	7.7	2.4	2.9	**64.8**	35.2	29.8	5.3
Nysa Kłodzka River at gauge Bystrzyca Kłodzka II													
Międzylesie	26.4	8.8	22.6	7.2	6.2	10.1	10.2	3.7	4.8	**57.8**	42.2	33.7	8.5
Międzygórze	22.6	7.9	23.3	9.0	9.7	8.0	7.6	6.0	5.9	**53.7**	46.3	34.4	11.9
Nysa Kłodzka River at gauge Kłodzko													
Międzylesie	26.9	8.9	24.5	6.0	6.3	9.7	10.3	3.7	3.7	**60.4**	39.6	32.3	7.3
Międzygórze	27.8	8.8	25.4	6.7	6.8	9.3	9.2	2.9	3.2	**62.0**	38.0	32.0	6.1
Bielice	26.7	10.2	27.5	8.5	8.2	7.2	6.5	2.3	2.9	**64.4**	35.6	30.5	5.1
Nowy Gierałtów	25.5	9.1	25.5	8.2	9.4	7.4	7.0	4.2	3.8	**60.0**	40.0	32.0	8.0
Ołdrzychowice	23.9	8.1	24.8	9.0	9.1	7.8	7.1	5.1	5.1	**56.8**	43.2	33.0	10.2
Zieleniec	24.3	7.9	21.0	7.3	7.1	9.6	10.2	6.4	6.1	**53.3**	46.7	34.2	12.5
Chocieszów	25.6	8.0	21.6	6.7	6.6	10.2	10.2	5.5	5.6	**55.2**	44.8	33.7	11.1
Polanica-Zdrój	22.4	7.5	19.2	7.6	7.7	9.9	10.1	7.3	8.2	**49.1**	50.9	35.4	15.5
Podzamek	22.5	8.3	24.1	9.2	9.2	8.3	8.0	5.1	5.3	**54.9**	45.1	34.7	10.4
Kłodzko	26.4	8.5	22.3	7.3	6.8	9.3	9.9	4.8	4.9	**57.1**	42.9	33.3	9.7
Wilczka River at gauge Wilkanów													
Międzygórze	25.6	9.1	26.3	8.3	9.4	7.1	6.2	4.1	3.8	**61.0**	39.0	31.1	7.9
Biała Lądecka River at gauge Lądek Zdrój													
Bielice	25.3	9.1	28.9	8.2	8.7	6.3	7.2	3.1	3.1	**63.3**	36.7	30.5	6.2
Nowy Gierałtów	26.8	8.7	25.5	8.3	7.9	8.3	8.3	3.1	3.0	**61.0**	39.0	32.8	6.1
Biała Lądecka River at gauge Żelazno													
Bielice	25.9	9.5	26.4	8.4	8.9	7.3	7.1	3.0	3.4	**61.9**	38.1	31.7	6.4
Nowy Gierałtów	27.1	8.9	24.3	6.3	6.3	10.0	9.3	3.4	4.4	**60.3**	39.7	31.9	7.8
Ołdrzychowice	21.5	7.3	20.5	7.4	7.8	10.3	10.1	7.5	7.5	**49.4**	50.6	35.6	15.0
Bystrzyca Dusznicka River at gauge Szalejów Dolny													
Zieleniec	28.6	9.6	27.4	6.9	7.2	7.3	8.0	2.4	2.4	**65.7**	34.3	29.5	4.8
Chocieszów	26.6	8.3	24.9	6.7	6.9	10.0	9.2	3.7	3.7	**59.8**	40.2	32.8	7.4
Polanica-Zdrój	23.4	7.4	21.1	7.8	7.5	10.0	10.9	5.9	6.0	**51.9**	48.1	36.2	11.9

It can be seen that in many cases precipitation in the upper parts of the catchment area is more synchronous with runoff from a given catchment recorded in profiles closing that catchment, while the degree of synchronicity between precipitation recorded in rain gauges located close to these profiles is noticeably lower (Table 4, Figure 5). Such cases include the Nysa Kłodzka River catchment controlled by water gauge Bystrzyca Kłodzka II, and the Biała Lądecka River sub-catchment controlled by water gauge Bystrzyca Dusznicka. This proves the key importance of precipitation in the upper parts of the catchment area for the formation of total runoff in the Nysa Kłodzka River catchment. This is due both to the volume of precipitation (it is higher in the upper parts of the catchment area, Figure 4A), as well as the shape and geological structure of the terrain-higher parts of the mountains being characterized by steeper slopes, which is translated into the transformation of most of the precipitation into surface runoff, reducing water retention and its subsequent transpiration.

Isolines of the synchronous occurrence of Pt and Rt in the Nysa Kłodzka River catchment controlled by gauge Kłodzko have a zonal distribution, with synchronicity values decreasing from south-east to north-west (Figure 5). This is disturbed in the north-western part of the area, due to the much lower (49.1%) synchronicity detected in gauge Polanica–

Zdrój in the Bystrzyca Dusznicka River catchment. The characteristic run of the isolines indicates stronger relationships between precipitation and runoff occurring in the southern and eastern parts of the area (the upper reaches of the Nysa Kłodzka River, and the Wilczka and Biała Lądecka catchments). This indicates a greater share of precipitation in this part of the area in the formation of the total annual runoff. In other words, it can be concluded that the eastern sub-catchments have larger contribution to the formation of the water resources in the study area. Interestingly, sub-catchments with higher synchronicity between precipitation and runoff have also relatively higher annual precipitation; an exception to this rule is the catchment area of the Bystrzyca Dusznicka River, where, with the highest precipitation in the whole study area (1277.8 mm at gauge Zieleniec), the synchronicity with water gauge Kłodzko reaches 53.3% (Table 4, Figure 5). The higher synchronicity of the eastern part of the study area can be attributed to its geology and soil permeability—it is built mostly of Precambrian metamorphic rocks, contrary to the Cretaceous sedimentary rocks prevailing in the western part. Moreover, higher synchronicity may result from relatively large slopes (30°) characteristic for the Śnieżnik Massif and the Bialskie Mountains [13].

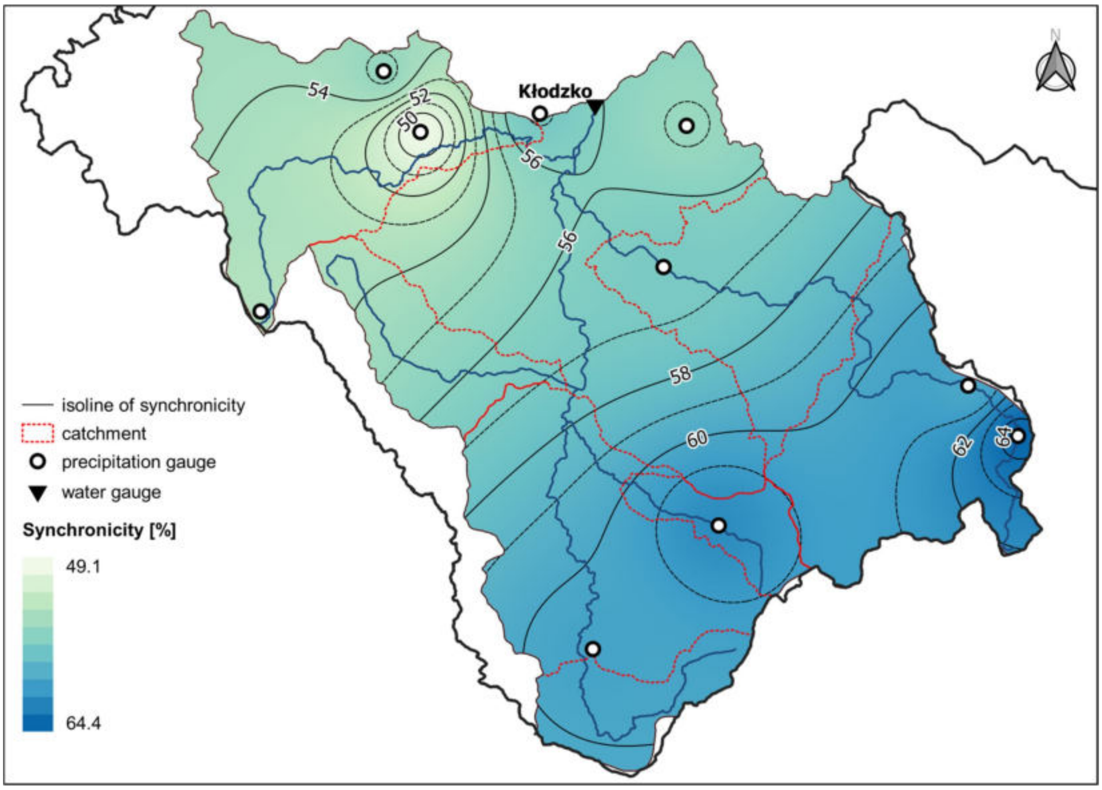

Figure 5. Synchronicity (%) of precipitation and runoff in the Nysa Kłodzka catchment closed by gauge Kłodzko.

4. Discussion and Conclusions

KV is one of the most important areas in Poland in terms of formation of the country's water resources. At the same time it is one of the areas most vulnerable to floods in Poland. While most recent studies have analyzed extreme hydro-meteorological events in KV, this research has concentrated on relations between average precipitation and runoff in that area. The study confirms the findings of Olichwer [18], who classified the Nysa Kłodzka River catchment as an area of high hydrological activity. That author analyzed the water resource abundance along the Nysa Kłodzka River in individual sub-catchments closed by river gauges Międzylesie, Bystrzyca Kłodzka II, and Kłodzko, respectively, focusing on the total and groundwater runoff. While such an approach allowed for determination of the long-term variability of water resources in KV, the adopted method of dividing the area made it impossible to detect differences between the eastern and western parts (sub-catchments) of the Nysa Kłodzka River catchment. As a result, it was also impossible to obtain the full picture of the complex hydrological relationships of this area. In contrast, the results of our study have proved that, in order to study water resources of a given area, analysis of their changes along the river may be insufficient. Thus, it seems to be justified to investigate water resources of each sub-catchment separately and analyze its impact on the formation of water resources in the whole area, of which it is a part.

It has been revealed that the eastern part of KV is more hydrologically active, while the western part is more hydrologically inert than the eastern one. By hydrological activity we mean contribution of precipitation in respective sub-catchments to runoff in the analyzed area (the Nysa Kłodzka River catchment closed by water gauge Kłodzko). It can be concluded that the eastern sub-catchments are richer in terms of water resources. It should be noted that these are rivers with frequent floods, including catastrophic floods [13]. The greater hydrological activity of the eastern (right) tributaries of the Nysa Kłodzka River is also evidenced by the greater variability of the flow of these rivers and greater abundance of water resources [19]. In the analyzed area, a diversified structure of both the water supply (precipitation) and runoff is also observed. While precipitation in the highest situated areas is similar, and even in the Bystrzyca Dusznicka sub-catchment (rain gauge Zieleniec) in the western part of the area is clearly higher (above 1270 mm), the total runoff is higher in the eastern sub-catchments. In the western part, the component of the total runoff from the snowmelt supply in the spring season is more significant, while in the eastern part the volume of the snowmelt runoff is similar, but the contribution of the summer rainfall grows considerably. That differentiation results from both the location and exposure of the sub-catchments, as well as the meteorological conditions triggering floods in the study area [9,10]. A consequence of the different water supply structure of the KV rivers is also a noticeable differentiation of the runoff regime. In the eastern part of the Nysa Kłodzka River catchment they represent the nival-pluvial type, while in the western part the nival type, with a much lower runoff in the summer season [19,29]. The KV rivers also differ in the terms of the stability and uncertainty of the flow regime characteristics [28,38,39]. Rivers in the eastern part of the area (as Wilczka, Biała Lądecka) and the upper Nysa Kłodzka are characterized by greater entropy (uncertainty) of the flow height than in the western part. On the other hand, the uncertainty of the monthly runoff distribution is higher in the case of the left (western) tributaries of the Nysa Kłodzka River, which proves their greater equalization in the annual cycle than in the case of the right (eastern) tributaries. The Bystrzyca Dusznicka River in the western part of the upper Nysa Kłodzka River catchment is also characterized by the lowest stability of the maximum monthly flows, which makes their uncertainty the highest.

This study is part of the analysis of the synchronous occurrence of hydro-meteorological phenomena using the copula function. In a similar approach, relationships between the amount of rainfall [40] and runoff [21,22,37,41], as well as between the flow and the amount of material transported by water [36,42,43], and also relations between snowmelt flood volume and peak discharge [44], and between the water levels of coastal lakes and sea water levels [45] were analyzed. These papers are evidence of successful application of the copulas in hydro-meteorological studies, but these methods also have their limitations. The major one is data availability and the necessity of using homogenous data sets of the same length and derived from the same observation period. In our research we faced some problems, including the lack of a rain gauge station located in the Bystrzyca River catchment (Figure 1), which made it impossible to analyze the Pt–Rt synchronicity in this catchment.

Another limitation refers to the used copula types; in our study, the bivariate (2D) copula functions were used, but there is a potential to use, e.g., the three-dimensional (3D) copulas, successfully applied in hydrological analyses. Multi-dimensional vine copulas were used for example in adopting a pair-copula function to analyze the encounter frequency of high–low annual runoff-sediment yields between different stations [43], developing probabilistic projections of multidimensional river flood risks at a convection-permitting scale [46], prediction of streamflow and the refinement of spatial precipitation estimates [47], or analyzing extreme storm surges induced by tropical cyclones [48].

The next significant issue, raised in the copula-related research, is uncertainty and reliability of the constructed models. It has to be noted that there is a lack of sufficient efforts, which should be made to uncover the underlying uncertainty, e.g., in the vine copula-based flood risk assessments [46]. On the other hand, there are proofs that probabilistic forecasting can be more informative (e.g., in providing the prediction uncertainty) than other deterministic models [47].

This research is a proposal to further develop and adapt the copula-based methodology in studies on the precipitation-runoff relationships and water resources of a given area. It also confirms the applicative value of the copula theory: The method presented can be used to evaluate the availability of water resources in areas playing the key role in their formation on different scales. Prospective related studies on water resources in KV should seek interdependencies in the precipitation and runoff patterns, and other relations between these variables (analyzed jointly and separately), also in the winter and summer half-years of the hydrological year.

To conclude, major highlights of the implemented research are as follows:

- Copulas can be used in studies on regional precipitation-runoff relations and to determine probabilistic values of analyzed variables.
- The precipitation-runoff relationship can be presented as the synchronous occurrence of these variables, and graphically depicted using isolines of synchronicity.
- The eastern tributaries of the Nysa Kłodzka River are more hydrologically active than the western ones, and they determine the amount of water resources of the study area.
- The regime features of rivers in KV depend on the type and distribution of precipitation over the year, and consequently on its relation with runoff in the sub-catchments of the Nysa Kłodzka River and its tributaries.

Author Contributions: Conceptualization, A.P. and D.W.; methodology, A.P., L.S. and D.W.; software, A.P.; validation, A.P., L.S. and D.W.; formal analysis, A.P.; investigation A.P. and D.W.; resources, D.W. and A.P.; data curation, A.P.; writing—original draft preparation, A.P.; writing—review and editing, A.P., D.W. and L.S.; visualization, A.P.; supervision, A.P. and D.W.; project administration, A.P.; funding acquisition, A.P., L.S. and D.W. All authors have read and agreed to the published version of the manuscript.

Funding: The research was carried out under the "GEO-INTER-APLIKACJE" project (No. POWR.03.02.00-00-I027/17), implemented at the Faculty of Geographical and Geological Sciences of Adam Mickiewicz University in Poznań, Poland.

Data Availability Statement: Data available on request due to restrictions e.g., privacy or ethical. The data presented in this study are available on request from the corresponding author.

Acknowledgments: We thank the editors and reviewers for their comments and suggestions which has significantly helped us to improve the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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Acta Geophysica (2022) 70:1301–1315
https://doi.org/10.1007/s11600-022-00765-z

RESEARCH ARTICLE - HYDROLOGY

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

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Received: 25 July 2021 / Accepted: 9 March 2022 / Published online: 21 April 2022

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 Lądecka 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

Edited by Dr. Senlin Zhu (ASSOCIATE EDITOR) / Dr. Michael Nones (CO-EDITOR-IN-CHIEF).

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water balance of landscape units, including soil moisture dynamics, evapotranspiration and runoff generation (Becker 2005). Water balance is the most important integral physiographic 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 physiographic 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 Miziński 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 Wrocław 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 been not 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 Wilczka (18.2 km), Bystrzyca (25.5 km), Biała Lądecka (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

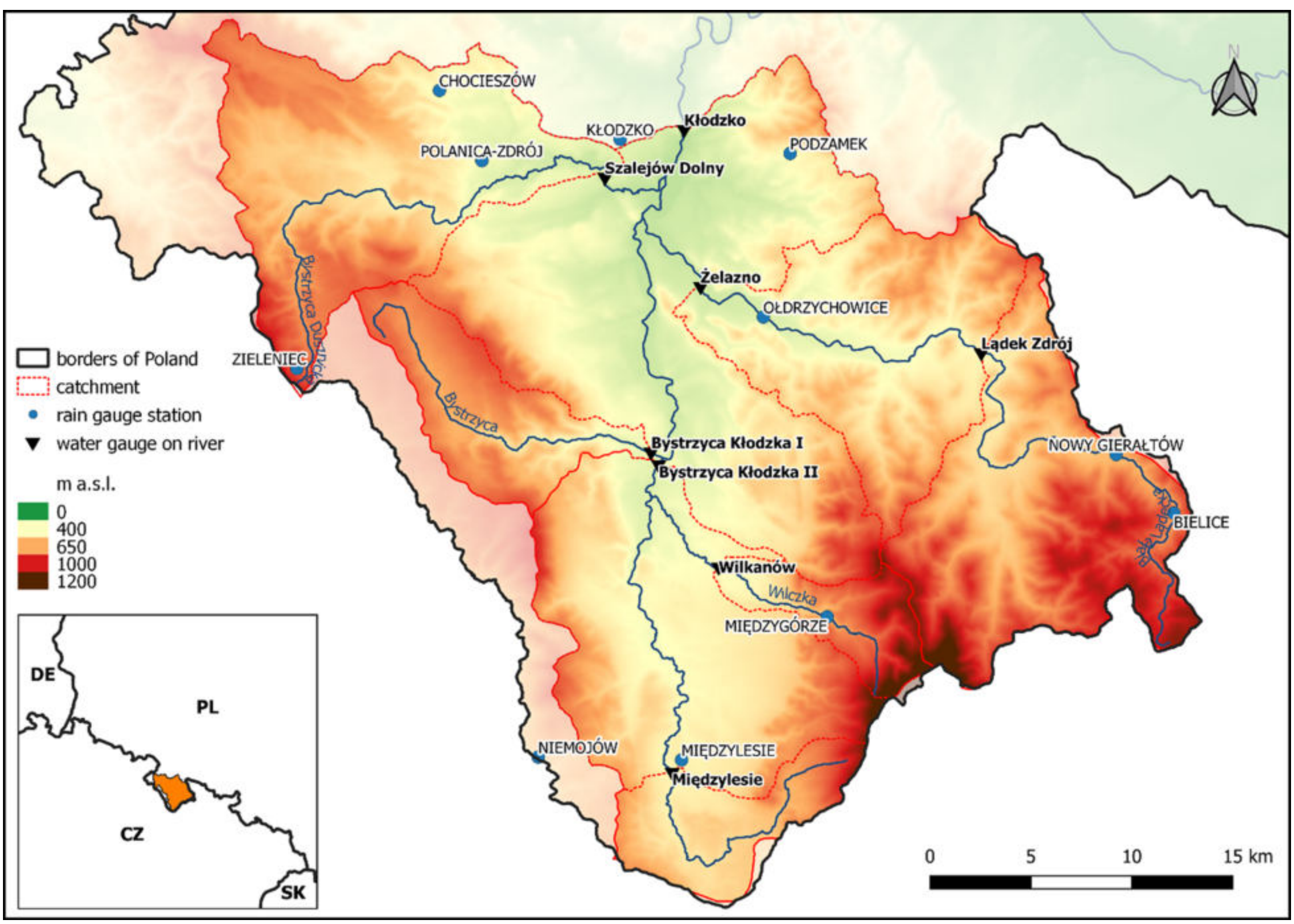

Fig. 1 Location of the water and rain gauges, boundaries of analysed catchments and geographical position of the study area in Poland

(the upper section of the Nysa Kłodzka above gauge Międzylesie, the Bystrzyca and the Bystrzyca Dusznicka rivers), and type 4—nival-pluvial regime (the Nysa Kłodzka River below gauge Międzylesie, the Biała Lądecka 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 Kłodzko 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 Kłodzka River catchment is situated in the so-called Kłodzko 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 Lądecka 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 Kłodzko (591.4 mm) (Table 1). Moreover, precipitation in KV exhibits apparent variations on the multiannual and monthly bases.

Runoff in the whole Nysa Kłodzka catchment controlled by gauge Kłodzko 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)
	Latitude	Longitude		
Bielice	50° 16′ N	17° 00′ E	695	1070.4
Chocieszów	50° 27′ N	16° 29′ E	405	694.3
Kłodzko	50° 26′ N	16° 36′ 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
Ołdrzychowice	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

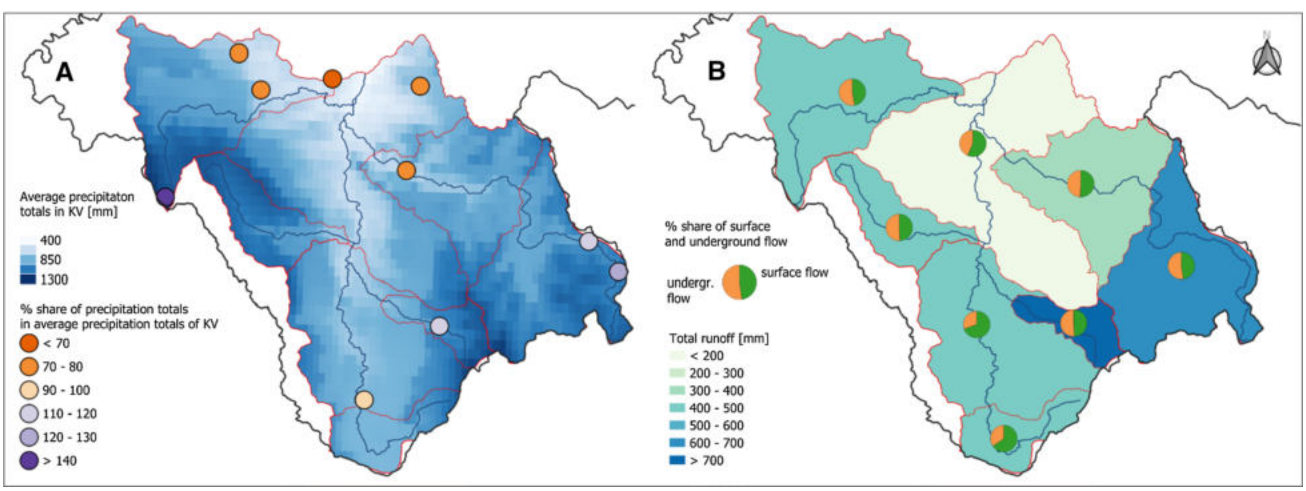

Fig. 2 Average precipitation (**A**) and runoff (**B**) in sub-catchments of KV in 1974–2013. On map *B* values of the total runoff refer to differential catchments, for example, to calculate the total runoff in the Biała Lądecka River sub-catchment controlled by gauge Żelazno, runoff recorded in gauge Lądek-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 Lądecka 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

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

River	Gauge	Coordinates		Altitude (m a.s.l.)	Catchment area (km^2)	Runoff depth (mm)	Areal precipitation[1] (mm)	River regime type[2]
		Lat	Long					
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	Lądek 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)

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 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_{RGS}) and average areal precipitation totals for the whole KV (P_{KV}), acquired through interpolation (see Sect. "Interpolation of data")—results are presented in Sect. "Synchronicity of precipitation",
- Runoff totals recorded in sub-catchments (R_{SC}) and runoff totals recorded in water gauge Kłodzko (R_{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_{SC}) and runoff: (1) recorded in water gauge closing the same sub-catchment (R_{SC}), and (2) recorded in water gauge Kłodzko (R_{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):

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

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

$$\begin{aligned}\mathrm{AIC} = &-2\log(\text{maximum likelihood for model})\\ &+ 2(\text{No. of fitted parameters}).\end{aligned} \tag{2}$$

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:

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

where u and v are marginal distributions, the θ, subscript of copula C, is the parameter hidden in the generating function ϕ, and ϕ 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 $\phi(t)$, and functional relationship of Kendall's $\tau\theta$ 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).

Table 3 Designation of sectors

Sector		X	Y
1	LA–LB	$X \leq A_{62.5\%}$	$Y \leq B_{62.5\%}$
2	LA–MB	$X \leq A_{62.5\%}$	$B_{62.5\%} < Y \leq B_{37.5\%}$
3	LA–HB	$X \leq A_{62.5\%}$	$Y > B_{37.5\%}$
4	MA–LB	$A_{62.5\%} < X \leq A_{37.5\%}$	$Y \leq B_{62.5\%}$
5	MA–MB	$A_{62.5\%} < X \leq A_{37.5\%}$	$B_{62.5\%} < Y \leq B_{37.5\%}$
6	MA–HB	$A_{62.5\%} < X \leq A_{37.5\%}$	$Y > B_{37.5\%}$
7	HA–LB	$X > A_{37.5\%}$	$Y \leq B_{62.5\%}$
8	HA–MB	$X > A_{37.5\%}$	$B_{62.5\%} < Y \leq B_{37.5\%}$
9	HA–HB	$X > A_{37.5\%}$	$Y > B_{37.5\%}$

where X = the values of x coordinates of generated points, Y = the values of y coordinates of generated points, $A_{62.5\%}/B_{62.5\%}$ = the value of variable A or B with a probability of exceedance of 62.5%, $A_{37.5\%}/B_{37.5\%}$ = 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 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 (HP_{SC}) is a synchronous event if in the same time unit "high" runoff from the sub-catchment (HR_{SC}) occurs.

If the synchronicity of P_{SC} and R_{SC} in a given catchment is 70%, this means that in seven out of ten years, the probable P_{SC} is within the same probability range as the probable R_{SC}.

In turn, the asynchronous event can be exemplified by the occurrence of HP_{SC} (e.g., a "20-year precipitation", $p = 5\%$) and the occurrence of LR_{SC} (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"/"asyn chronicity" refers to the synchronous/asynchronous occurrence (co-occurrence probability) of the analysed values.

Structure of water balance

The structure of the water balance can be estimated based on the runoff coefficient (C) (Dynowska and Pociask-Karteczka 1999), which represents the integrated effects of infiltration, evaporation, retention, and interception, all of which affect the runoff volume. The runoff coefficient is the ratio of the amount of water flowing out of the catchment area in the time unit to the amount of water that at the same time falls down in the form of precipitation within the catchment boundaries. It determines the percentage of precipitation that flows out of a catchment. These calculations were made not only for the empirical average values, but also for the probable ones.

Results

Synchronicity of precipitation

The spatial analysis of the obtained results of the P_{RGS} and P_{KV} 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 P_{KV} occurs in rain gauges located in the southern (Międzylesie) 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. "Synchronous and asynchronous occurrence"). The most synchronous in relation to P_{KV} is precipitation at gauge Międzylesie (> 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, Międzylesie is also precipitation gauge where average precipitation is the closest to areal precipitation from

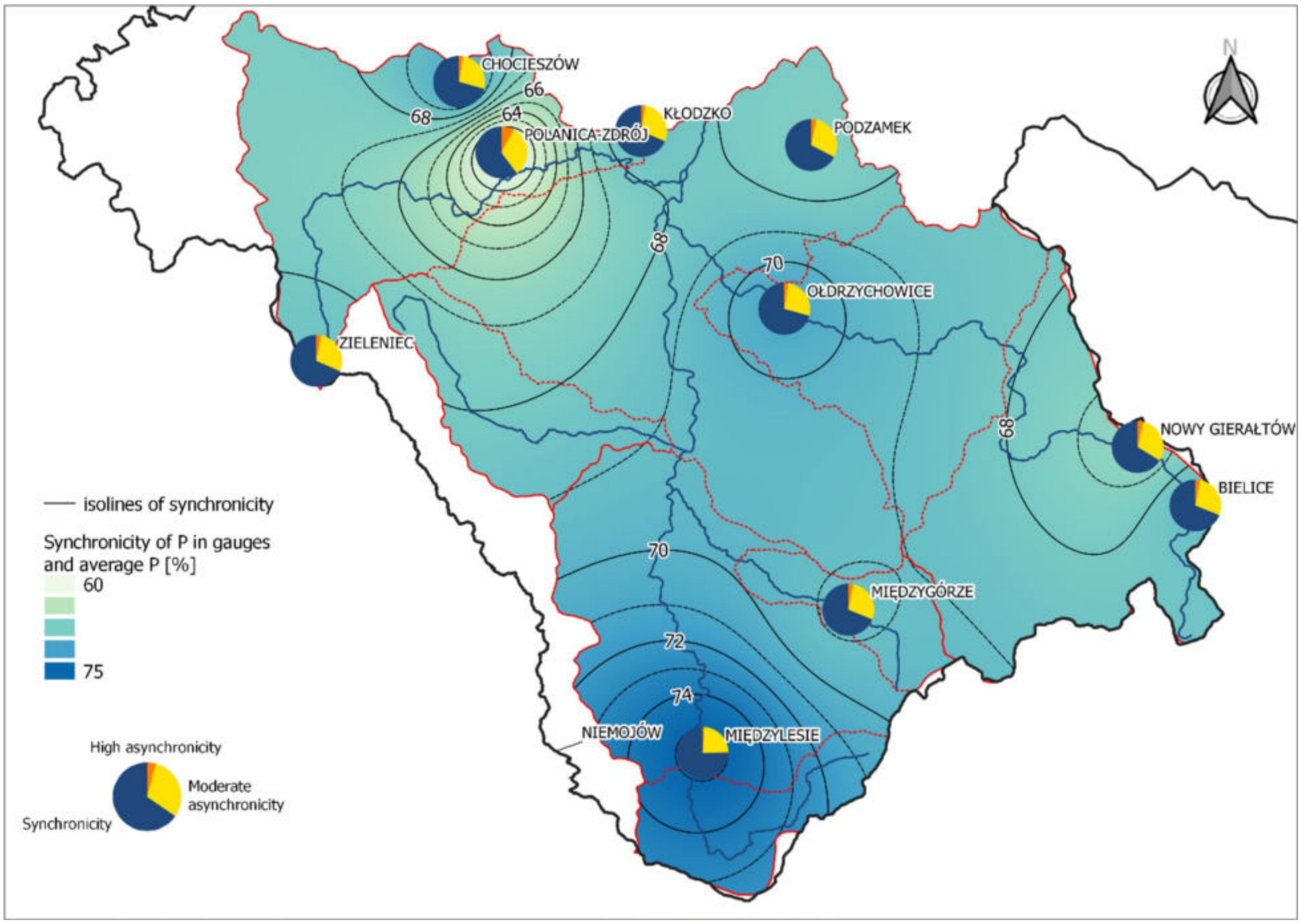

Fig. 3 Synchronicity of precipitation recorded in rain gauge stations (P_{RGS}) and areal average precipitation in KV (P_{KV})

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 Lądecka 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 Lądecka 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 Lądecka River plays a special role—relatively high

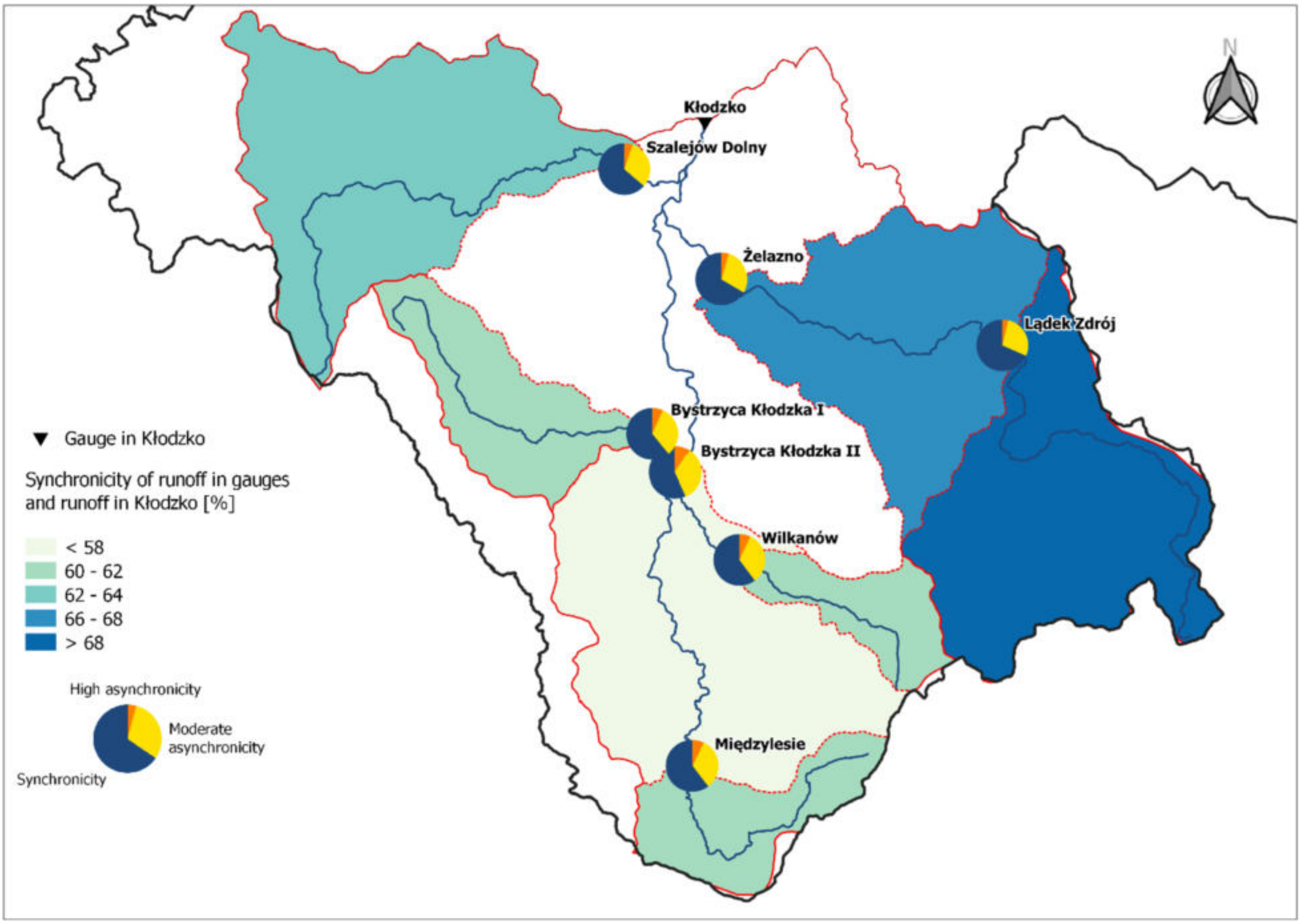

Fig. 4 Synchronicity of runoff in sub-catchments (R_{SC}) and total KV runoff (R_{KV})

synchronicity (Lądek-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 Lądecka 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

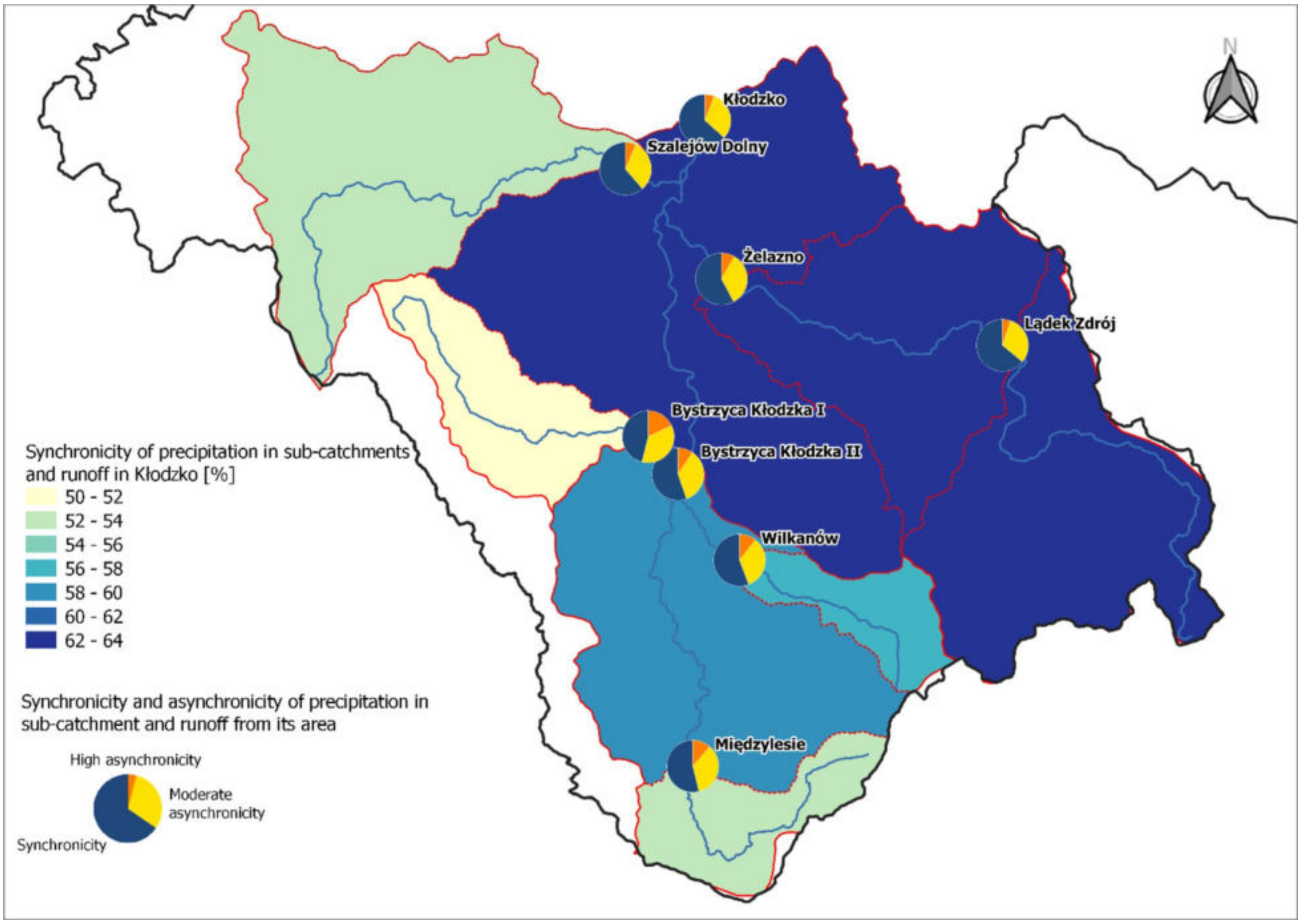

Fig. 5 Synchronicity of areal precipitation for sub-catchments (P_{SC}) and runoff from its area (R_{SC}, pie charts) and areal precipitation for sub-catchments (P_{SC}) and total KV runoff (R_{KV}, choropleth map—colours of the sub-catchments)

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 Lądecka River (controlled by gauge Lądek-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 Lądecka 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 Lądecka 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,

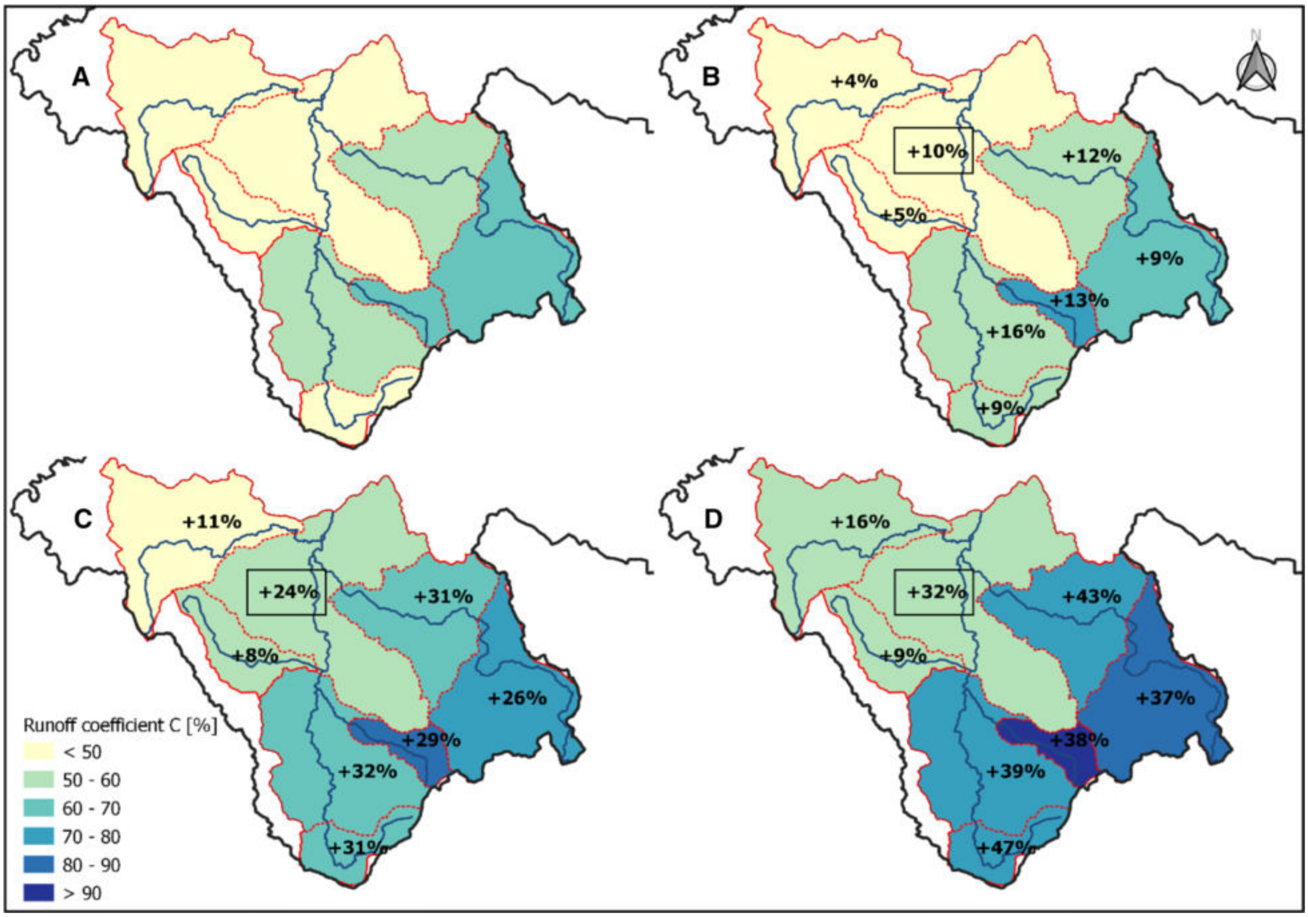

Fig. 6 Spatial differentiation of runoff coefficient C, calculated on the basis of average precipitation and runoff totals (**A**), probable values of precipitation and runoff with the probability of exceedance of 10% (**B**), 1% (**C**) and 0.2% (**D**). Values on maps B, C and D (e.g. "+11%") present increase of the runoff coefficient value in comparison to average values. The value in a frame refers to the whole KV

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 Lądecka rivers, controlled by gauge Lądek-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% (gauge Kłodzko) to over 140% (gauge Zieleniec) of the average precipitation (Fig. 2A). This has also been confirmed by the calculated P_{RGS}–P_{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 Międzylesie is synchronous with the whole catchment rainfall in 75% (Fig. 3). The study has also showed that the degree of synchronicity between P_{RGS} and P_{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 Lądecka 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 Lądecka 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 Lądecka) 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 Lądecka 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 Lądecka River sub-catchment, which shows the strongest synchronicity in terms of the R_{SC}–R_{KV} (Fig. 4) and P_{SC}–R_{KV} (Fig. 5) relationships, despite the relatively lower P_{SC}–P_{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

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 Lądecka 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 Lądecka 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 Lądecka 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.

Acknowledgements The research was carried out under the “GEO-INTER-APLIKACJE” project (No. POWR.03.02.00-00-I027/17), implemented at the Faculty of Geographical and Geological Sciences of Adam Mickiewicz University in Poznań, Poland. Adam Perz is a scholarship holder of the Adam Mickiewicz University Foundation for the academic year 2021/2022. Authors would like to thank Reviewers for their valuable comments, which allowed to significantly improve the research and the manuscript. The Authors also acknowledge the help of Dr. Bartosz Czernecki in interpolation of precipitation data.

Funding The APCs were co-financed from the funds of „UNIWERSYTET JUTRA" (No. POWR.03.05.00-00-Z303/17) and "GEO-INTER-APLIKACJE" (No. POWR.03.02.00-00-I027/17) projects.

Availability of data and material Data used in the manuscript were obtained from the resources of the 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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Journal of Hydrology: Regional Studies 44 (2022) 101214

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh

Copula-based geohazard assessment – case of flood-prone area in Poland

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ARTICLE INFO

Keywords:
Kłodzka Valley
Summer floods
Flood hazard
Archimedean copula
Synchronicity
Floods Directive

ABSTRACT

Study region: Upper Nysa Kłodzka River (NKR) catchment, Poland
Study focus: Floods are one of the most important geohazards, because they can cause negative consequences for human health and life, environment, cultural heritage, economic activity and infrastructure. This study presents a comprehensive assessment methodology of the summer (rainfall-driven) flood hazard applying a probabilistic approach. The research considers interdependencies between flood characteristics (peak flow and flood wave volume) and their relations with the cumulative rainfall recorded before flood events in the upper NKR catchment, one of the most flood-prone areas in Poland. The research is based on daily values of rainfall and river flow for the warm half-year (i.e. from the 1st May to the 31st October) in the multi-annual period 1971–2019.
New hydrological insights for the region: The research allowed to formulate the spatio-temporal rules and dependencies between significant floods characteristics and rainfall, e.g. in terms of the coincidence of flood waves occurrence along the main water course and its tributaries. The research contributes to solving flood management issues in concentric river systems in mountainous areas, such as the upper NKR catchment.

1. Introduction

The environment is a complex system of interrelated elements and processes taking place between them. These processes are sometimes extreme in nature, causing changes and losses to both the natural environment and infrastructure, and may also pose a direct and indirect threat to human health and life (Rutgersson et al., 2022). One of the most important geohazards are floods, especially because, as indicated by Blöschl et al. (2020), we are currently in an exceptional flood-rich period in terms of timing of flood occurrence, magnitudes and spatial extent in Europe. Generally, there are many studies proving that future extreme hydrological events in Europe will be more frequent and adverse due to climate change (Lehner et al., 2006; Dankers and Feyen, 2008; Kundzewicz et al., 2013; Alfieri et al., 2015; Kundzewicz et al., 2018; IPCC et al., 2022), however, there are also regional differences in identified trends or projections (Paprotny, Morales-Nápoles, 2017; Blöschl et al., 2019; Bertola et al., 2020; Rutgersson et al., 2022; Venegas-Cordero et al., 2022).

In general, extreme floods can cause negative consequences for human health and life, the environment, cultural heritage,

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https://doi.org/10.1016/j.ejrh.2022.101214
Received 7 June 2022; Received in revised form 7 September 2022; Accepted 14 September 2022
Available online 20 September 2022

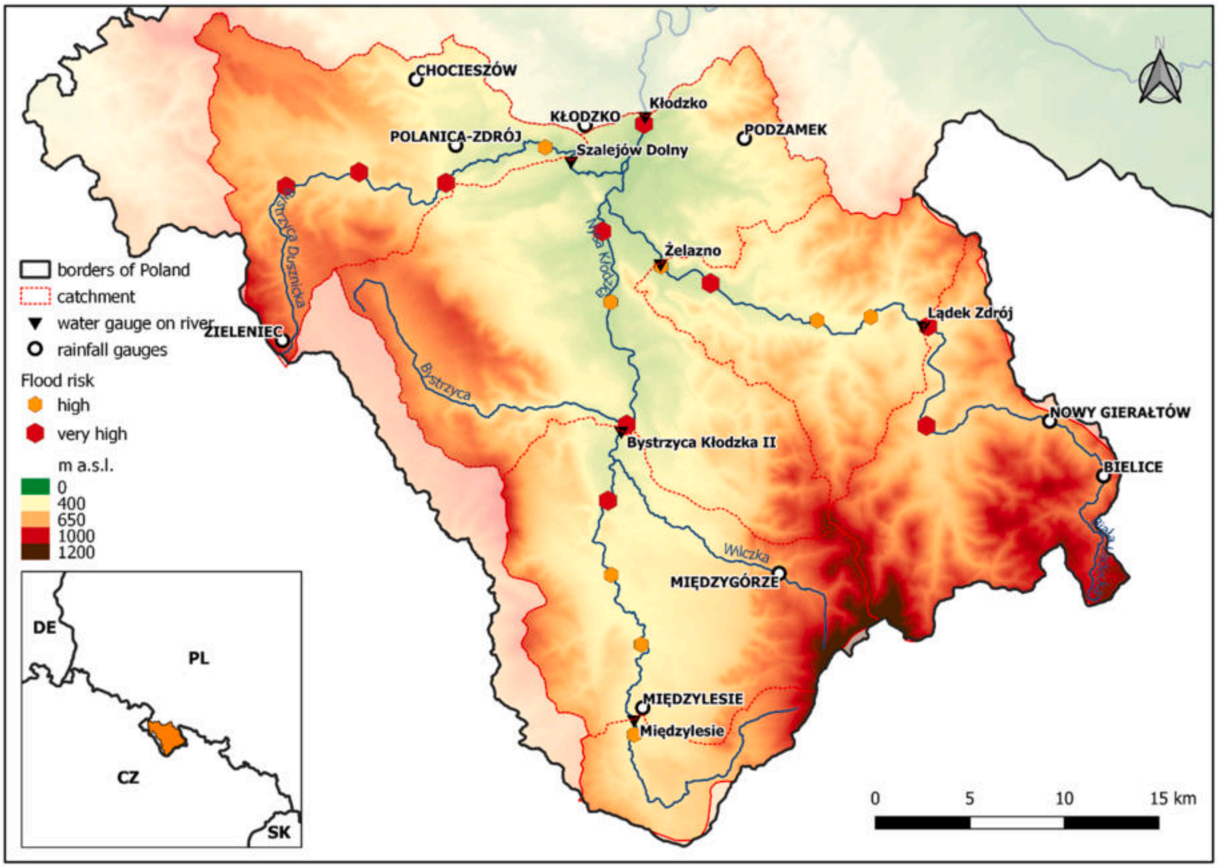

Fig. 1. Study area (the upper NKR catchment), location of river gauges and rainfall stations and towns of high or very high flood risk identified. On the basis of Dubicki et al. (1999), Kundzewicz et al. (2009), OVFMP Coordination Unit (2021).

economic activity and infrastructure (Floods Directive, 2007; Graf, 2021). Their impact is complex and often affect simultaneously many parts of the natural and artificial environment. Hajdukiewicz et al. (2018) and Bucała-Hrabia et al. (2020) analyzed the influence of extreme floods on geomorphological changes in stream channels, they can have also powerful positive influence e.g. for habitat heterogeneity (Tockner et al., 2000) or 'self-cleaning' of river ecosystem (Niedzielski et al., 2018). On the other hand, extreme floods can spread pollutants stored in environmental hotspots, such as wastewater treatment plants, waste handling facilities, contaminated sites etc. (Arrighi et al., 2018; Bedryj et al., 2018) or temporally increase concentration and load of the transported suspended solids, leading to a reduction in the population of living organisms (Ciupa et al., 2021). However, probably most commonly analyzed is the risk of extreme floods connected with human health and life (Ruin et al., 2008, Zahran et al., 2008, Deng et al., 2022) or infrastructure, housing, cultural heritage etc. (e.g. Dottori et al., 2016, Koks et al., 2019, Albrecher et al., 2020, Paprotny et al., 2020, Figueiredo et al., 2021, Paprotny et al., 2021).

Methods based on copulas are getting more and more popular in flood hazard (e.g. Ozga-Zielinski et al., 2016, Candela and Aronica, 2017, Salvadori et al., 2018) and risk (e.g. Jongman et al., 2014, Albrecher et al., 2020) assessment. Copula functions allow to combine interrelated variables (such as peak flow and flood volume) and conduct the analysis in probabilistic approach (Candela and Aronica, 2017). They allow also e.g. to assess compound flood hazard from riverine and coastal interactions (Couasnon et al., 2018; Xu et al., 2019). In terms of flood hazard management, the results presented by Salvadori et al. (2018) suggest, that, for checking the adequacy and the functionality of existing water works, a statistical (multi-variate) survey represents a necessary step, though it may not be sufficient. There is still a research gap in multi-variate hazard analysis and using it in following risk (or multi-hazard) assessment. Blöschl et al. (2020) indicate that process-based models that capture the physical mechanisms in the atmosphere and rainfall-runoff transformation on the land surface, including the role of precipitation, soil moisture, snowmelt and seasonality in flood generation in both recent and historical times, will be an essential component of flood-risk assessment tools in a changing climate. Flood hazard is not only connected with a range of inundated area and water depth, but also with flood duration (Vorogushyn et al., 2010; Curran et al., 2018), flood volume (De Michele et al., 2005; Salvadori et al., 2018) and peak flow (Garrote et al., 2021) – these three characteristics are interconnected (Rahimi et al., 2021) and decisive in determining the flood hazard level. Standard flood hazard mapping usually do not consider all of these aspects – there is the necessity of developing the hazard assessment methods, which are not only based on the hydrological or hydraulic modelling (Ozga-Zielinski et al., 2018; Baldassarre et al., 2020; Petroselli et al., 2020), and addresses the need of rational water management considering the whole catchment, rather than focusing on local inundation zones.

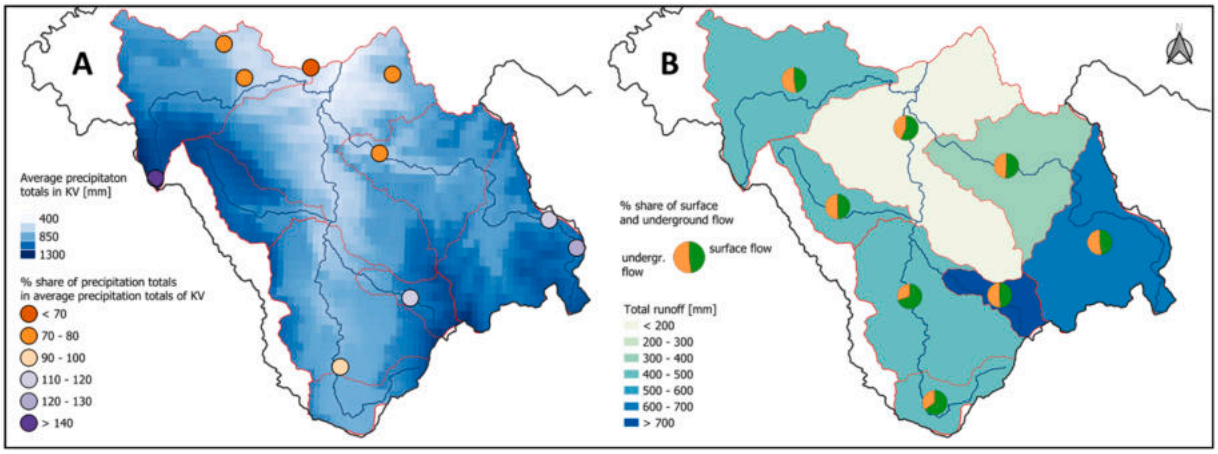

Fig. 2. Average precipitation (A) and runoff (B) in sub-catchments of the upper NKR catchment in 1974–2013.
After Perz et al. (2022).

This study is focused on a comprehensive assessment methodology of the summer (rainfall-driven) flood hazard in probabilistic approach on the example of the upper Nysa Kłodzka River (NKR) catchment in the Sudety Mountains, which is one of the most flood-prone parts of the Odra River basin. This research considers interdependencies between flood characteristics (peak flow and volume) and their relations with rainfall recorded before a given flood event, and fits in the identified research gap, in contrast to previous studies (Perz et al., 2021, 2022), which attempted to identify relations between annual precipitation totals and total runoff in terms of water resources formation in the upper NKR catchment. Moreover, in comparison to previous works, this research is based on the extended in time data sets (for period 1971–2019) considering extreme flows and event-based precipitation sums, and tries to present the issue of flood hazard (not general water resources) in a broader spatial context and draw attention to its complex nature within the upper NKR catchment.

2. Study setting, data and methods

2.1. Study area

In order to introduce the proposed methodology, one of the most flood-prone areas in Poland has been selected – the upper NKR catchment (Fig. 1). The warm half of the year is the most exposed season for natural hazards in Poland, and most of them have a meteorological nature or origin – they most prominently include intensive rainfall, which triggers floods, primarily in summer (Pociask-Karteczka et al., 2018). In general, mountainous basins are highly prone to have extreme precipitation events, both in terms of total volume and intensity (Stoffel et al., 2016). These rain-induced floods can be subdivided into those generated by convective rains with high intensity, and those generated by long-lasting frontal precipitation with lower intensity (Pociask-Karteczka et al., 2018). The NKR catchment, as a mountainous area, is also at risk of flash flood occurrence (Piotrowski et al., 2006).

The upper NKR catchment is a part of area in Poland where average annual number of floods is the highest (>10 per year) (Bartnik, Jokiel, 2012). The Sudety Mountains tributaries of the Odra River, after the Carpathian rivers flowing into the Vistula River, have the highest flood potential index values in Poland (Jokiel, Bartnik, 2017; Magnuszewski, 2021) and noticeable differences in terms of stability and uncertainty of runoff regime (Wrzesiński, 2013). One of the earliest documented examples of floods in Poland is the NKR's flood of July 1310, which killed more than 1500 people (Pociask-Karteczka et al., 2018). Flood of July 1997, which had its origin in the NKR catchment, is considered to be the most disastrous flood ever in the Odra River basin (Kundzewicz et al., 2009), and it is called the "Millennium Flood". The possibility of coincidence of flood wave on NKR with flood wave on Odra River poses one of the highest hydrological threats in the whole country (Kundzewicz, 2012; Pociask-Karteczka et al., 2018). Bednorz et al. (2019) point to the deposition of river beds in older formations and the concentric arrangement of the river network of the Kłodzko Valley as conditions favoring the formation of high water levels and flood waves on the rivers of the region.

Taking into account the above-described flood potential of the NKR catchment, there have been conducted numerous case studies focusing on the rainfall-runoff relations in the Kłodzka Valley (KV) during the extreme floods. For example, Szalińska et al. (2008) attempted to estimate the precipitation value causing summer floods in the middle Odra River basin. Łach (2009) analyzed the history of summer flood floods in the KV during eight centuries, and based on historical and observational data in the 20th century determined the frequency of extreme floods in the Kłodzko region. Łach (2012) analyzed the role of torrential rains and floods in modeling the relief of KV and the western mountain ranges of the Eastern Sudety Mountains, and concluded that in the 20th century floods transforming its valley-bottom environment occurred every 18 years on average. Rutkowska et al. (2016) carried out a comparative analysis of design discharges estimated from both daily maximum flows and daily mean flows for four mountainous catchments located in the upper NKR basin. They found a meaningful level of differences between daily maximum and mean design discharges and

Table 1
Basic characteristics of rainfall stations.

Rain Gauge Station	Coordinates		Altitude (m a.s.l.)	Average precipitation (mm)		
	Latitude	Longitude		Annual	Cold half-year (Nov.-Apr.)	Warm half-year (May-Oct.)
Bielice	50°16′ N	17°00′ E	695.00	1074.6	399.5	675.1
Chocieszów	50°27′ N	16°29′ E	405.00	695.8	256.6	439.1
Kłodzko	50°26′ N	16°36′ E	356.00	583.6	174.5	409.1
Międzygórze	50°13′ N	16°46′ E	585.00	1007.3	383.6	623.7
Międzylesie	50°09′ N	16°40′ E	450.00	856.8	378.8	478.0
Nowy Gierałtów	50°18′ N	16°57′ E	635.00	985.0	353.7	631.3
Podzamek	50°25′ N	16°43′ E	400.00	715.4	219.7	495.7
Polanica-Zdrój	50°25′ N	16°31′ E	390.00	703.3	267.7	435.6
Zieleniec	50°19′ N	16°23′ E	845.00	1225.1	572.9	652.2

between the rate of change of flood magnitude. Niedzielski and Miziński (2017) proposed a new system for computing the multi-model ensemble predictions of water levels, known as HydroProg, which was applied in the process of real-time modelling and forecasting of river flow in the upper NKR catchment. Stodolak et al. (2018) analyzed the influence of rain temporation on the results of the rainfall-runoff model in the Bystrzyca River catchment, a left-bank tributary of the NKR. Jeziorska and Niedzielski (2018) used TOPMODEL for modeling the streamflow dynamics in the upper NKR catchment. Bednorz et al. (2019) classified synoptic conditions of summer floods in Polish Sudety Mountains.On that basis five cyclonic circulation patterns of different origin, and various extent and intensity, responsible for heavy, flood-triggering precipitation in the Sudety Mountains, were assigned. Dumieński et al. (2020) analyzed the adaptability level of municipalities in the NKR sub-catchment to flood hazard and identified municipalities located in the KV (municipalities of Międzylesie, Bystrzyca Kłodzka, Kłodzko and Kłodzko city) as showing moderate to very high level of the integrated flood risk. The same municipalities, however, were classified as ones with the highest adaptability to flood hazard in the entire NKR catchment.

In order to underline the importance of flood risk in this area, it should be mentioned that there are being constructed, among others, four dry flood reservoirs in the KV, under the Odra-Vistula Flood Management Project (OVFMP), co-financed by the International Bank for Reconstruction and Development (also called the World Bank) and the Council of Europe Development Bank (OVFMP Coordination Unit, 2021). The location of the main problem areas on the analyzed water courses in the KV, taking as the criterion for selecting key problem areas population density, presence of compact residential developments, concentration of industry, flooding of schools, hospitals, care homes, hotels and guest houses, wastewater treatment plants, water intakes, main road and railway communication routes, are presented in the Fig. 1.

Relatively higher precipitation is recorded in the mountainous areas (in southern, western and eastern parts of the study area) (Figs. 1 and 2A), whereas noticeably lower values are recorded in its less elevated, central and northern parts (Fig. 2A) (Perz et al., 2022).

In most of the analysed catchments the structure of runoff is similar—the share of the underground and surface runoff is about 50% each. However, the upper section of NKR (controlled by river gauges Międzylesie and Bystrzyca Kłodzka II), differs from this pattern—in that part of the study area the surface runoff noticeably prevails (Fig. 2B) (Perz et al., 2022).

The extensive description of the upper NKR catchment and its hydrological conditions is provided by Anon (2021) and in our previous works – please refer to Perz (2019), Perz et al. (2021), (2022).

2.2. Data

The research was conducted on the basis of the data obtained from the Institute of Meteorology and Water Management – National Research Institute in Warsaw, Poland. The data sets included daily values of rainfall (R) and river flow (Q) for the warm half-year (i.e. from May to October) in the multi-annual period 1971–2019 (sub-daily data are not available). The only exception is rainfall station Zieleniec, because the precipitation data have been collected there since 1974. The basic statistics for the nine rainfall stations and six river gauges selected for the analysis are presented in Tables 1 and 2, respectively, and their location is shown in Fig. 1.

2.3. Methods

2.3.1. Data preparation

The first stage of data preparation, decisive for the course of further analyzes, was the selection of significant summer precipitation surges from the multi-annual period covered by the study (1971–2019, see chapter 2.2). In the selection of flood waves, two threshold values of the flows were used: $Q_{99\%}$ and $Q_{90\%}$, calculated from the set of daily flows for the summer half-year (1st May-31st October) in the entire multi-annual period. The analysis used floods with flood peak flow (FPQ) above the $Q_{99\%}$ value (Fig. 3). If the limit value was exceeded for several days in a row, it was assigned to one extreme event, the date of which was assumed to be the peak flow day. The flood volume (FWV) of each of the selected flood waves was also calculated. This was done in two variants - for the total wave volume (FWV_t) and the wave volume above the $Q_{90\%}$ threshold ($FWV_{Q90\%}$, Fig. 3). In this study, the flood wave duration (FWD) was understood as the number of days with flows above the $Q_{90\%}$ threshold. The flood volume was expressed in [m^3] and converted into the outflow layer in [mm].

Table 2
Basic characteristics of river gauges on analyzed rivers.

River	Gauge	Coordinates		Altitude (m a.s.l.)	Catchment Area (km^2)	Average flow (m^3/s)			Runoff depth (mm)			River Regime Type[a]
		Latitude	Longitude			Annual	Cold half-year (Nov.-Apr.)	Warm half-year (May-Oct.)	Annual	Cold half-year (Nov.-Apr.)	Warm half-year (May-Oct.)	
Nysa Kłodzka	Międzylesie	50°09′ N	16°39′ E	426.00	49.7	0.69	0.89	0.49	437.6	280	156.6	2
	Bystrzyca Kłodzka II	50°17′ N	16°39′ E	338.00	260.0	3.82	4.71	2.94	463.9	283.3	179.7	4
	Kłodzko	50°26′ N	16°39′ E	281.00	1084.0	12.58	13.89	11.26	365.9	200.4	165.2	4
Biała Lądecka	Lądek Zdrój	50°20′ N	16°52′ E	421.00	166.0	3.33	3.13	3.53	633.1	295.1	338.4	4
	Żelazno	50°22′ N	16°40′ E	317.00	305.0	4.77	4.46	5.07	492.8	228.7	264.3	4
Bystrzyca Dusznicka	Szalejów Dolny	50°25′ N	16°34′ E	305.00	175.0	2.10	2.49	1.70	378.0	222.7	154.8	2

[a] Types of river regime: 2 – nival moderately developed, 4 – nival-pluvial (Source: Perz, 2019; Wrzesiński, 2016, 2021, modified)

The next step was to determine the sum of daily precipitation from the five days preceding the FPQ of the flood wave. From these data, the cumulative rainfall (CR) was calculated for respectively 24, 48, 72, 96, and 120 h preceding FPQ (hereinafter referred to as CR_{24}, CR_{48}, CR_{72}, CR_{96}, CR_{120}, respectively).

A summary of the statistics related to the selected flood waves and the preceding rainfall is presented in Chapter 3.1.1.

2.3.2. Application of copula functions

To analyze the interrelations between hydro- and meteorological variables the bivariate copulas were used. Many case studies prove that copula functions are a useful and powerful tool in analysis of hydrological and meteorological data. In the proposed methodology copulas were applied to identify probability of synchronous and asynchronous occurrence (i.e. synchronicity and asynchronicity) of the analyzed variables. Generally, they can be divided into two groups – synchronicity between:

1. selected flood characteristics (results presented in Sections 3.1.2 and 3.1.3),
2. rainfall and floods characteristics (results presented in Sections 3.2.1 and 3.2.2).

In the first group there were analyzed relations between:

- **FPQ** of **NKR** in Kłodzko (**FPQ_K**) and flow measured in five river gauges closing the sub-catchments (**Q_{SC}**),
- **FPQ** and **FWV** in every river gauge.

and in the second group:

- **FPQ** measured in river gauges and **CR** measured in rainfall stations,
- **FWV** and **CR** measured in rainfall stations.

Firstly, for each analyzed data set the best matching statistical distribution type was selected among the following ones: Weibull, Gamma, Gumbel and log-normal. Estimation of distribution parameters was conducted using the maximum likelihood method. The Akaike Information Criterion (AIC) (Akaike, 1974) was used to check goodness-of-fit of the distribution in the data sets:

$$AIC = N\log(MSE) + 2p, \tag{1}$$

where MSE is the mean square error, N is the sample size, and p is number of fitted parameters or.

$$AIC = -2\log(ML) + 2p\cdot \tag{2}$$

where ML is maximum likelihood for model, and p is number of fitted parameters.

The best fitted distribution type is the one having the minimum AIC value (Akaike, 1974).

The next step was to construct the joint distribution of chosen data series (see bullets above) using copulas. Generally, a bivariate Archimedean copula can be defined as:

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

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

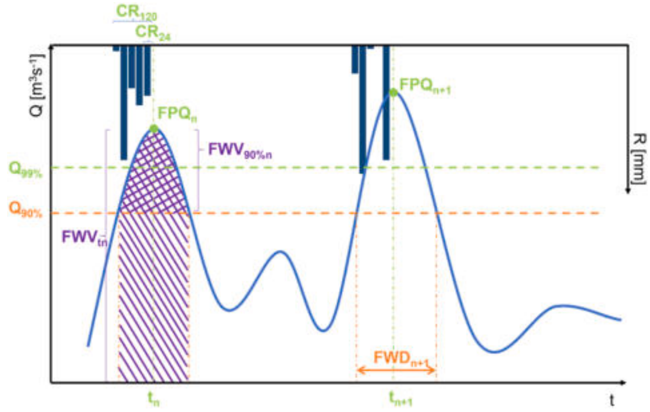

Fig. 3. Schematic visualisation of selecting procedure, based on the 99th / 90th percentile flow ($Q_{99\%}$ / $Q_{90\%}$), of the flood characteristics, i.e. the Flood Peak Flow (FPQ), Flood Wave Volume (FWV), Flood Wave Duration (FWD), and Cumulative Rainfall (CR).

The Clayton, the Gumbel-Hougaard and the Frank copula families (which are one-parameter Archimedean copula functions) were applied in this research (Table 3).

The goodness-of-fit of the joint distribution was checked using AIC.

For each pair of data sets 5,000 hypothetical values were randomly generated on the basis of previously computed statistical distribution parameters of marginal distributions. They were used to select the best-fitted copula family for a given data series pair and next for an appropriate copula forming. Such a step allows to avoid obtaining distorted (or even reverse) results, what was proven by e. g. Gu et al. (2018). Based on empirical value pairs (red points in Fig. 4) for particular years and generated hypothetical points (marked with gray in Fig. 4), graphs with probability curves (expressed in return periods) were generated (Fig. 4).

Then, the generated value pairs were analyzed based on 62.5% and 37.5% probability levels (Zhang et al., 2014; Gu et al., 2018). According to these levels, nine sectors were designated (Table 4), which represent different relations between probable values of analyzed variables.

The degree of synchronicity is the percent share of generated points in sectors 1, 5, and 9 (Fig. 4, Table 4) in the 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).

To put it differently, the probability of synchronous and asynchronous occurrences (i.e. synchronicity and asynchronicity) of analyzed variables were determined through a calculation of the threshold values of probability ranges:

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

The sum of synchronicity and asynchronicity is 100%. In each case, only hydrologically related rainfall stations and river gauges were analyzed.

Synchronicity of FPQ_K or FWV_K with CR (i.e. analyzing data from one river gauge and data from several rainfall stations) allowed interpolation of the results. The interpolation was performed by means of the Inverse Distance Weighted (IDW) method, based on the concept of distance weighting (Chen, Liu, 2012).

To synchronous occurrence can be demonstrated by a situation when a given flood event, in which FPQ is in the range of MFPQ, is caused by MCR_{72}. It would be an asynchronous occurrence, if it was caused by LR_{72} or HR_{72}. The synchronicity measure can be understood as a probability of occurrence of synchronous situation. For instance, 70% synchronicity means that (from the statistical point of view) the synchronous situation occurs seven times per every 10 events on average.

Synchronicity and asynchronicity, described also as e.g. "probability of synchronous or asynchronous occurrence", "synchronous-asynchronous encounter probability" or "rich-poor / dryness-wetness encounter probability", were applied in the analysis of the co-occurrence probability of runoff and sediment load (Zhang et al., 2014, You et al., 2019, Qian et al., 2021), precipitation (Zhang et al., 2012; Guan et al., 2021), mean or maximum annual flow / runoff (Gu et al., 2018; Mitkova and Halmova, 2019; Perz et al., 2020; Sobkowiak et al., 2020; Xu et al., 2022), precipitation and runoff (Perz et al., 2021, 2022), or coastal lakes and sea water level (Plewa et al., 2019).

Table 3
Copula function, parameter space, generating function *Φ(t)*, and functional relationship of Kendall's τ_θ with a copula parameter for selected single-parameter bivariate Archimedean copulas.

Copula Family	$C_\theta(u,v)$	Generator $\phi(t)$	Parameter $\theta \in$	Kendall's τ_θ
Clayton	$max\left(\left(u^{-\theta}+v^{-\theta}-1\right)^{-1/\theta},0\right)$	$\frac{1}{\theta}(t^{-\theta}-1)$	$(-1,\infty)\ \{0\}$	$\tau=\theta/(2+\theta)$
Gumbel-Hougaard	$exp\left\{-\left[(-lnu)^{\theta}+(-lnv)^{\theta}\right]^{1/\theta}\right\}$	$(-\ln t)^{\theta}$	$[1,\infty)$	$(\theta-1)/\theta$
Frank	$\frac{-1}{\theta}ln\left[1+\frac{(e^{-\theta_u}-1)(e^{-\theta_v}-1)}{e^{-\theta}-1}\right]$	$-ln\frac{e^{-\theta t}-1}{e^{-\theta}-1}$	$(-\infty,\infty)\ \{0\}$	$1+4[D_1(\theta)-1]/\theta$

where D_k *(x)* is Debye function, for any positive integer k,

$$D_k(x)=\frac{k}{k^x}\int_0^x\frac{t^k}{e^t-1}dt. \tag{4}$$

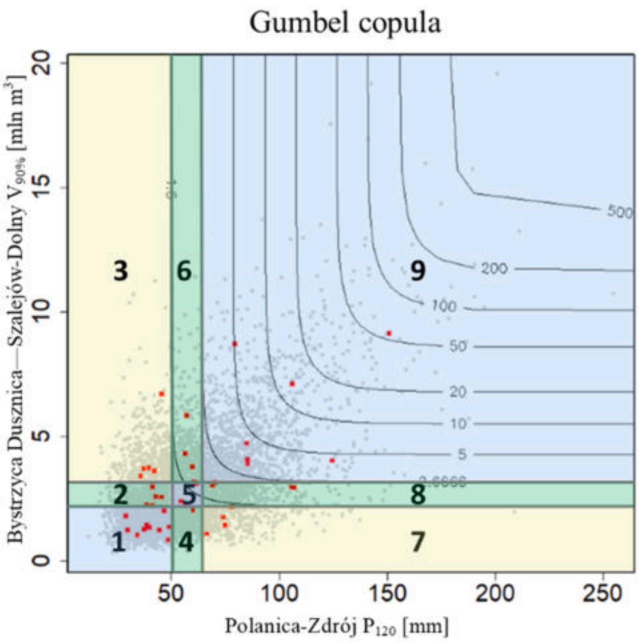

Fig. 4. Sample chart with delimited sectors.

Table 4
Designation of sectors.

Sector		Relation type[a]	X	Y
1	LA–LB	Synchronicity	$X \le A_{62.5\%}$	$Y \le B_{62.5\%}$
2	LA–MB	Moderate asynchronicity	$X \le A_{62.5\%}$	$B_{62.5\%} < Y \le B_{37.5\%}$
3	LA–HB	High asynchronicity	$X \le A_{62.5\%}$	$Y > B_{37.5\%}$
4	MA–LB	Moderate asynchronicity	$A_{62.5\%} < X \le A_{37.5\%}$	$Y \le B_{62.5\%}$
5	MA–MB	Synchronicity	$A_{62.5\%} < X \le A_{37.5\%}$	$B_{62.5\%} < Y \le B_{37.5\%}$
6	MA–HB	Moderate asynchronicity	$A_{62.5\%} < X \le A_{37.5\%}$	$Y > B_{37.5\%}$
7	HA–LB	High asynchronicity	$X > A_{37.5\%}$	$Y \le B_{62.5\%}$
8	HA–MB	Moderate asynchronicity	$X > A_{37.5\%}$	$B_{62.5\%} < Y \le B_{37.5\%}$
9	HA–HB	Synchronicity	$X > A_{37.5\%}$	$Y > B_{37.5\%}$

where X = the values of x coordinates of generated points, Y = the values of y coordinates of generated points, $A_{62.5\%}$ / $B_{62.5\%}$ = the value of variable A or B with a probability of exceedance of 62.5%, $A_{37.5\%}$ / $B_{37.5\%}$ = 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 analyzed in this research, i.e. CR or FPQ or FWV (see details on the beginning of this section).
[a] compare with sector colors in Fig. 4

Table 5
Parameters of the analyzed summer flood waves with Q> $Q_{90\%}$ in 1971–2019.

River-gauge	Number of waves N	Flood-wave duration [FWD] Q>Q_{90} [days]	Flood outflow [mm]			Share of the flood wave outflow in the summer half-year outflow [%]		
			maximum	minimum	average	maximum	minimum	average
Nysa Kłodzka - Międzylesie	48	6.6	167.4	4.0	21.9	34.8	2.0	9.5
Nysa Kłodzka - Bystrzyca Kłodzka	45	6.9	251.8	6.8	35.7	46.3	2.7	12.7
Nysa Kłodzka - Kłodzko	45	7.6	114.1	5.0	22.2	32.7	2.1	9.3
Biała Lądecka - Lądek-Zdrój	35	7.3	367.8	6.0	52.3	38.1	1.6	9.9
Biała Lądecka - Żelazno	29	8.6	334.0	6.1	45.0	45.5	2.0	10.5
Bystrzyca Dusznicka - Szalejów Dolny	43	7.9	52.2	4.7	17.8	19.7	1.8	8.5

3. Results

3.1. Characteristics of the selected flood events and relations between them

3.1.1. Floods statistics

In the analyzed multi-annual period, a total of 245 flood waves were identified on the studied rivers in the summer half-year (Table 5). The largest number of waves was recorded in 1971 (16), 1980 (19), 1997 (17) and 2010 (16). As a rule, flood waves appeared synchronously on the main river - NKR and its tributaries. The year 1995 was an exception, when 13 flood waves on the main river were not accompanied by waves on the tributaries. The lowest number of flood waves (29) was recorded on the Biała Lądecka River (gauge Żelazno), while the highest (48) on NKR (gauge Międzylesie) – Table 5. The flood wave duration on the rivers studied was similar, and ranged from 6.6 to 8.6 days on average. During the flood waves, the average and highest values of runoff were relatively the highest on the Biała Lądecka River, the right tributary of NKR. On average, the runoff during the analyzed flood waves was high and accounted for approximately 10% of the total runoff in the summer half-year. The size of some waves, e.g. during the flood in 1997, is evidenced by the fact that the shares of the flood wave runoff then accounted for almost a half of the total runoff in the summer half-

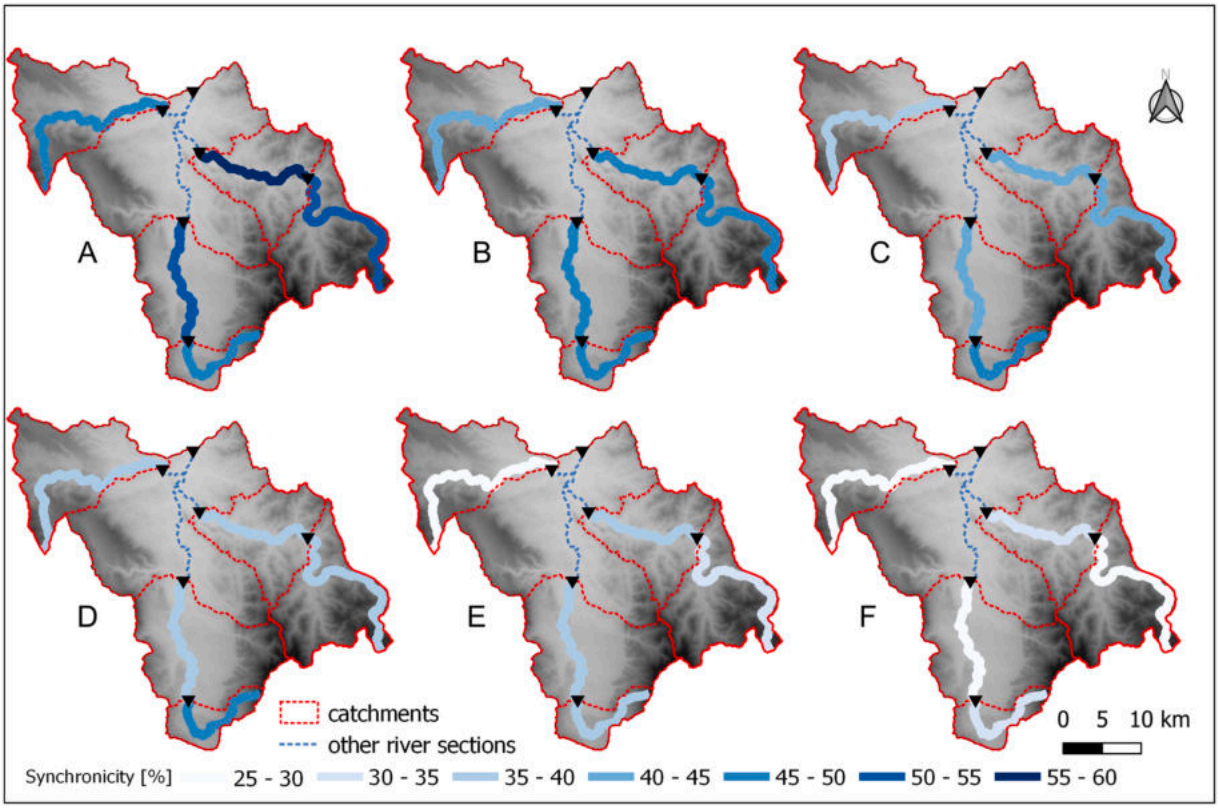

Fig. 5. Synchronicity of flood peak flows in Kłodzko (FPQ_K) and flood peak flows in sub-catchments (FPQ_{SC}) in (A) FPQ_K occurrence day and (B) one day, (C) two days, (D) three days, (E) four days and (F) five days before FPQ_K.

Table 6
Synchronicity of flood peak flow (FPQ) and flood wave volume (FWV) in sub-catchments.

River – gauge	FPQ-FWV_t [%]	FPQ-$FWV_{90\%}$ [%]
Nysa Kłodzka – Międzylesie	51.5	53.3
Nysa Kłodzka – Bystrzyca Kłodzka	58.4	59.1
Nysa Kłodzka – Kłodzko	63.4	67.6
Biała Lądecka – Lądek-Zdrój	55.7	58.7
Biała Lądecka – Żelazno	58.7	67.9
Bystrzyca Dusznicka – Szalejów Dolny	55.6	61.1

year.

3.1.2. Synchronicity of FPQ in Kłodzko and FPQ in sub-catchments

Synchronicity between FPQ in Kłodzko (FPQ_K) and Q in the sub-catchments (Q_{SC}) was calculated in six variants, i.e. from the "zero" day (FPQ_K occurrence day, Fig. 5A) to the fifth day before the FPQ_K occurrence (Fig. 5F). Generally, synchronicities increase from the fifth day before FPQ_K to the "zero" day. This indicates a rapid movement of the flood waves in the upper NKR catchment and the flood wave formation in the closing gauge Kłodzko. The highest synchronicity (> 55%) was determined for Q in gauge Żelazno (Biała Lądecka), values exceeding 50% were also recorded in gauges Lądek-Zdrój (Biała Lądecka) and Bystrzyca Kłodzka (NKR) (Fig. 5A). The increasing synchronicity along NKR may result from the fact that the flood wave in the upper NKR section (after Międzylesie) started to form even before the "zero" day. This is confirmed by the values of synchronicity remaining on this section at a similar level in the period from the third day before FPQ_K to the "zero" day (Fig. 5A-D). The Wilczka River, the right tributary of NKR (not included in this study), and the Bystrzyca Kłodzka River flowing into it before the river gauge, may have an additional impact. The Q synchronicity of the Bystrzyca Dusznicka River, in contrast to the second analyzed NKR tributary (Biała Lądecka), did not exceed the 50% level in any of the analyzed variants (Fig. 5A-F). This proves the low probability of a significant flood on NKR in Kłodzko caused by the inflow of the Bystrzyca Dusznicka River water.

3.1.3. Synchronicity of FPQ and FWV

Synchronicity between FPQ and FWV in individual river gauges was calculated in two variants: FWV_t and $FWV_{90\%}$ (Table 6). The FPQ-FWV_t synchronicity ranges from 51.5% (gauge Międzylesie) to 63.4% (gauge Kłodzko), while the FPQ-$FWV_{90\%}$ synchronicity from 53.3% (gauge Międzylesie) to 67.9% (gauge Żelazno, with only slightly lower synchronicity was recorded in gauge Kłodzko - 67.6%) (Table 6). The synchronicity of FPQ-FWV in both variants increases along the NKR course, as is the case in the Biała Lądecka River. Similar relationship was determined for FWD (see Table 5). This indicates the transformation of the flood wave along the course of the rivers of the upper NKR catchment. Low synchronicity in gauge Międzylesie may result from the mountainous character of the highest section of the NKR (Fig. 1) – such conditions are favorable to flood wave formation (most of the selected flood waves refer to gauge Międzylesie – see Table 5) with a relatively high FPQ, but with a short FWD and relatively low FWV (flash flood). Additionally, the wide valley of the NKR efficiently transforms flood waves on the river section from Międzylesie, through Bystrzyca Kłodzka, to Kłodzko. Historical flood events show, that if NKR is not supplied by its tributaries (mostly Biała Lądecka and Bystrzyca Dusznicka), then it remains a low-flooding river.

3.2. Rainfall and significant floods

3.2.1. Synchronicity of CR and FPQ

The FPQ synchronicity recorded in individual river gauges (FPQ_{SC}) for CR_{24}, CR_{48}, CR_{72}, CR_{96}, CR_{120} is presented in Fig. 6. Analyzing the dependence of FPQ_{SC} on CR (Fig. 6, detailed results given in Table A1), it can be concluded that generally CR_{24} is characterized by the lowest synchronicity with FPQ_{SC}, and only for Lądek-Zdrój it exceeds 50%. This is due to the fact that among the selected floods, there were cases that reached FPQ after the end of rainfall (i.e. 24 h before recording FPQ, no rainfall was recorded). The synchronicity of FPQ at gauge Międzylesie with rainfall at station Międzylesie in none of the CR variants (CR_{24} - CR_{120}) exceeds 50%. It should be noted that in this case the river gauge and the rainfall station are close to each other (Fig. 1), so that this weather station may not sufficiently reflect the rainfall situation in the NKR catchment after Międzylesie, which seems to be confirmed by the higher values of synchronicity with rainfall in Międzylesie with FPQ in Bystrzyca Kłodzka. It was also determined for this station that in the CR_{48} variant, precipitation in Międzygórze (located in the Wilczka River catchment, a small right tributary of NKR) had their maximum synchronicity, and only in the CR_{72} variant, it was precipitation in Międzylesie (52.4%) (Fig. 6, Table A1). The higher value of synchronicity with rainfall in the Wilczka River catchment, and the occurrence of the maximum synchronicity already for the CR from 48 h, may indicate a large (and quick in the context of the flood-causing rainfall occurrence) impact of this inflow on the flood situation at NKR in Bystrzyca Kłodzka.

An interesting situation, although fundamentally different, also applies to the Biała Lądecka River. For river gauge Lądek-Zdrój, we see a generally continuous increase in the FPQ-CR synchronicity, from CR_{24} to CR_{120} (Fig. 6, Table A1). For gauge Żelazno located below (and thus closing the larger catchment area), a clear jump in synchronicity was observed for the relationship with rainfall measured in Nowy Gierłatów in the CR_{72} variant (compared to CR_{48}), while the maximum synchronicity was recorded in the CR_{96} variant (72.6%). This is the highest value of FPQ_{SC} synchronicity with CR (Fig. 6, Table A1). The synchronicity of FPQ in Żelazno with

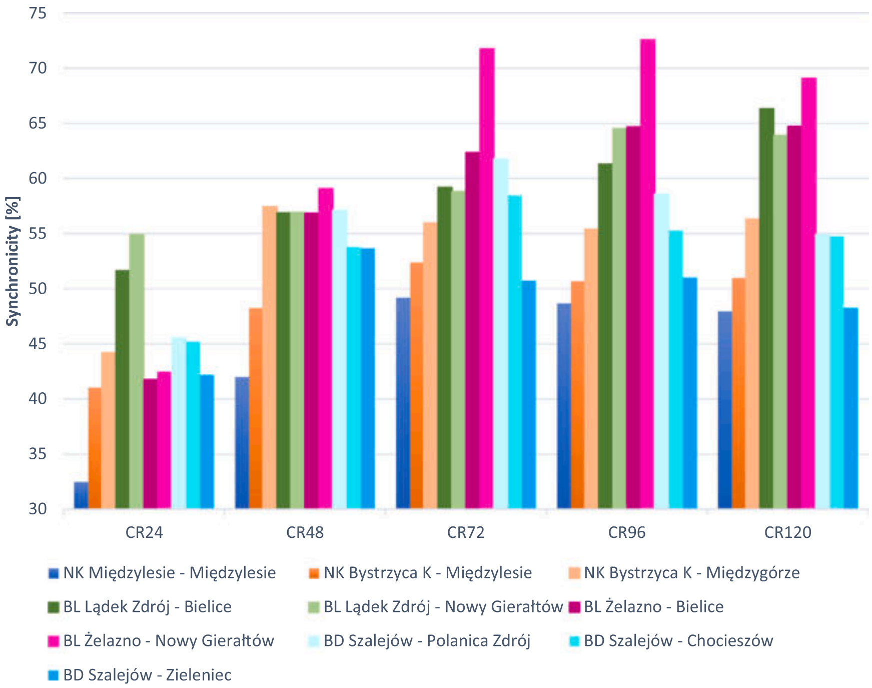

Fig. 6. Synchronicity of cumulative rainfall (CR) from 24 to 120 h before flood event and flood peak flow in sub-catchments of the study area (FPQ_{SC}).

CR in Bielice is the same in variants CR_{96} and CR_{120} (64.7%), and in other variants of CR it is lower.

There are as many as three meteorological stations in the Bystrzyca Dusznicka sub-catchment (Fig. 1). For two of them, the maximum synchronicity between FPQ_{SC} and CR was recorded for the CR_{72} variant (Polanica-Zdrój - 61.8%, Chocieszów - 58.5%), while for station Zieleniec, located in the highest part of that sub-catchment, for the CR_{48} variant (53.7%) (Fig. 6, Table A1).

The analysis of synchronicity between FPQ_{SC} and CR reveals some spatial relationships. In general, FPQ_{SC} is more synchronous with CR in the Biała Lądecka sub-catchment than the partial catchments of NKR (after Międzylesie and Bystrzyca Kłodzka) and the Bystrzyca Dusznicka sub-catchment. In this sub-catchment, the CR-FPQ relationship is also of a different nature, as it has the greatest strength in the CR_{96} or CR_{120} variants, while in the other sub-catchments it is the case in the CR_{48} and CR_{72} variants. The case of a pair of river gauge Międzylesie and rainfall station Międzylesie proves that not every meteorological station reflects well the precipitation conditions in a given sub-catchment area.

The analysis of the dependence of FPQ_K on CR measured at individual meteorological stations allowed for the interpolation of the synchronicity (Fig. 7). In the CR_{24} variant (Fig. 7A), it can be seen that the 24-hour rainfall preceding the significant flood event are asynchronous, which is consistent with the situation in the sub-catchments (see Fig. 6). On the other hand, CR_{48} in the Biała Lądecka sub-catchment shows a clear relationship with FPQ_K and reaches the maximum value of synchronicity among all analyzed variants (>57% for station Nowe Gierałtowice) (Fig. 7B, Table A1). In the subsequent time steps (Fig. 7C-E), the synchronicity of CR with FPQ_K in the western part of the study area increases, while in the eastern part slightly decreases. An exception for the eastern part of the NKR catchment is station Podzamek, located in its immediate catchment area, where in variants CR_{72}, CR_{96} and CR_{120} the synchronicity increases about 53.5% (Fig. 7C-E, Table A1). The highest asynchronicity in each variant was recorded for the cumulative rainfall measured at station Chocieszów (Fig. 7), located in the Bystrzyca Dusznicka sub-catchment. "High asynchronicity" for this station ranges from 19 (R_{120}) to 27% (R_{48}) (Table A1). This means that it is very likely that "low-high" or "high-low" situations will occur (on average once every 4–5 significant flood in Kłodzko).

3.2.2. Synchronicity of CR and FWV

The $FWV_{90\%}$ synchronicity on individual river gauges ($FWV_{90\%\text{-}SC}$) for CR_{24}, CR_{48}, CR_{72}, CR_{96}, CR_{120} is presented in Fig. 8 and Table B1. When analyzing these relationships, it can be concluded that they are generally the lowest in the CR_{24} variant, with the exception of rainfall stations located in the Bystrzyca Dusznicka sub-catchment, which remain at a similar level in all CR variants. Interestingly, the lowest CR-$FWV_{90\%\text{-}SC}$ synchronicity in this sub-catchment is shown on station Zieleniec, where the highest annual sums of precipitation in the entire NKR catchment are recorded (Table 1, Fig. 2).

The highest synchronicities in the CR_{48} - CR_{120} variants are recorded in the Biała Lądecka sub-catchment (gauge Żelazno, station Nowy Gierałtów), while in the CR_{24} variant in the aforementioned Bystrzyca Dusznicka sub-catchment (station Chocieszów).

Compared to the results of CR-FPQ_{SC} synchronicity (Section 3.2.1), the generally calculated CR-$FWV_{90\%\text{-}SC}$ relationships are less synchronous (the highest values do not exceed 60%) (Fig. 8, Table B1). However, different spatial relationships can also be detected, e.

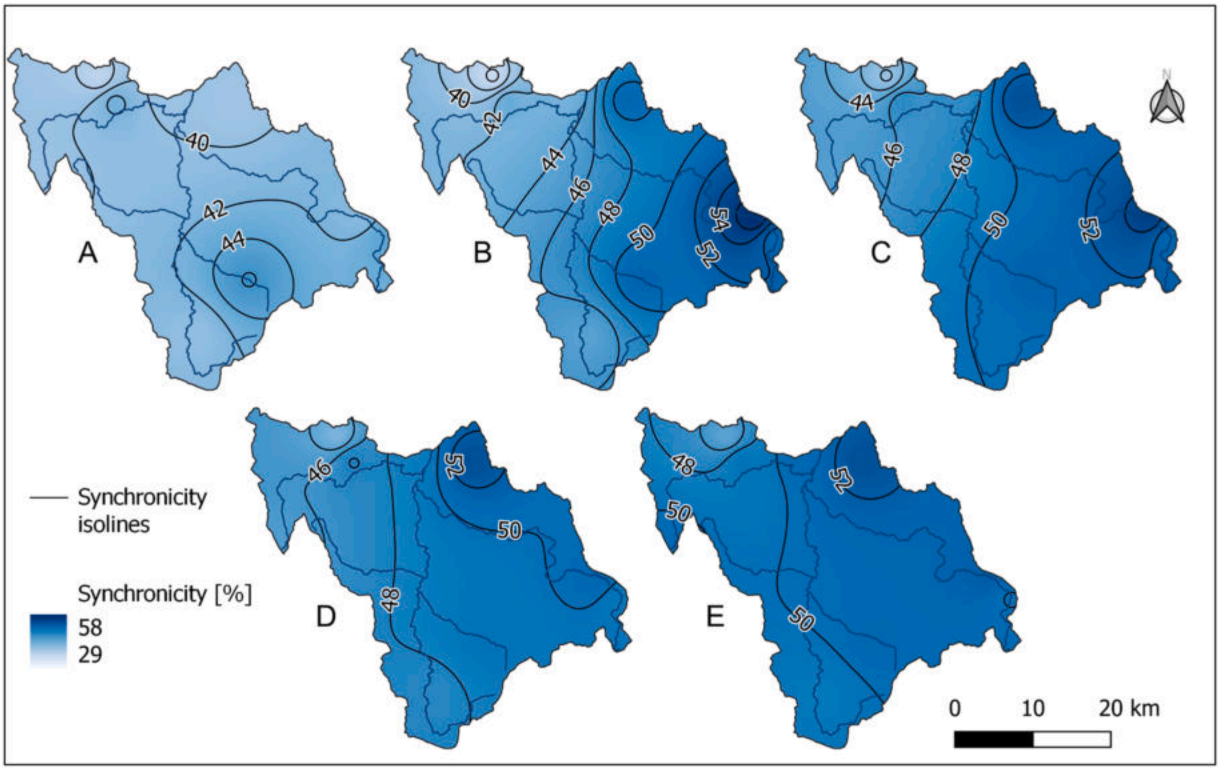

Fig. 7. Synchronicity of flood peak flow in Kłodzko (FPQ_K) and cumulative rainfall from 24 to 120 h before flood event: (A) CR_{24}, (B) CR_{48}, (C) CR_{72}, (D) CR_{96} and (E) CR_{120}.

g. a relatively high and even level of the CR synchronicity in the Bystrzyca Dusznicka sub-catchment with $FWV_{90\%-SC}$. As in the case of the CR-FPQ_{SC} synchronicity, the CR synchronicity with $FWV_{90\%-SC}$ in the Biała Lądecka sub-catchment increases with the successive time steps of accumulation of rainfall, and the highest synchronicities are recorded for the pair Żelazno-Nowy Gierałtów. The maxima of CR-$FWV_{90\%-SC}$ synchronicity in individual pairs are usually recorded in the variants CR_{96} and CR_{120}. Similarly to the case of CR-FPQ_{SC} synchronicity (see Fig. 6), also here the lowest values were calculated for Międzylesie.

As in the case of the CR-FPQ_K relationship (Section 3.2.1), also the results of the CR-$FWV_{90\%-K}$ synchronicity were interpreted (Fig. 9). As a rule, in this case higher values of synchronicity are recorded in the south-eastern and eastern parts of the NKR catchment. The CR_{48} variant (Fig. 9B) shows a clear advantage of the CR synchronicity with $FWV_{90\%-K}$ recorded in the sub-catchments of the eastern tributaries of NKR.

The highest value ($>$ 57.5%) was calculated for weather station Nowy Gierałtów in the Biała Lądecka sub-catchment in the CR_{120} variant (Fig. 9E, Table B1), while slightly lower values are also recorded there in the CR_{72} (Fig. 9C) and CR_{96} (Fig. 9D) variants. In turn, the lowest CR-$FWV_{90\%-K}$ synchronicity in each variant is characteristic of station Chocieszów in the Bystrzyca Dusznicka sub-catchment (similarly to the CR-FPQ_K relationship - see Fig. 7).

4. Discussion and conclusions

The research has confirmed the flood-prone character of the upper NKR catchment. For instance, just for river gauge Kłodzko 45 summer flood waves exceeding $Q_{99\%}$ within 49 years were identified (Table 5). Additionally, application of the proposed methodology allowed to formulate a few general spatio-temporal rules and dependences, such as: (1) flood wave on the Biała Lądecka River is more probable to cause a flood wave in the same probability ranges on the NKR, than on the Bystrzyca Dusznicka River; and the upper NKR section (river gauge Międzylesie) can be responsible for building up a flood wave in Kłodzko several days before "day zero" (Fig. 5), (2) FPQ is more synchronous with $FWV_{90\%}$ than with FWV_t (Table 6), (3) despite the mountainous character of the study area and a fast movement of flood waves in the upper NKR catchment, their size in the sub-catchments (in terms of FPQ and FWV) mostly depends on CR from 3 to 5 days before the flood event occurrence (Figs. 6 and 8), (4) the 24-hour rainfall preceding a flood event is mostly asynchronous in relation to the flood size (Figs. 6, Fig. 7A, Fig. 8, Fig. 9A), (5) the 4–5-day CR preceding a flood event are more

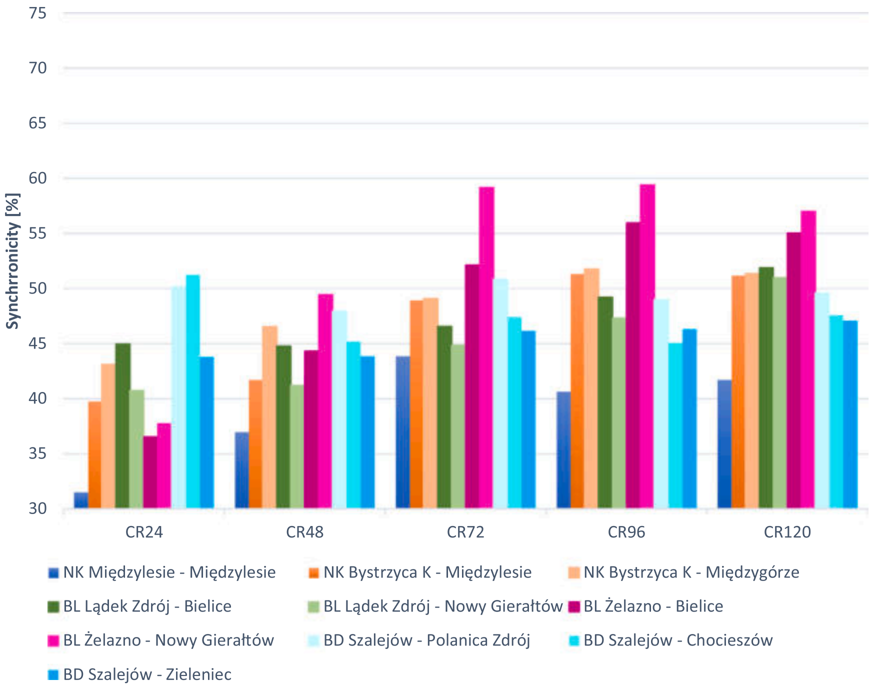

Fig. 8. Synchronicity of cumulative rainfall (CR) from 24 to 120 h before flood event and flood wave volume in sub-catchments of the study area ($FWV_{90\%-SC}$).

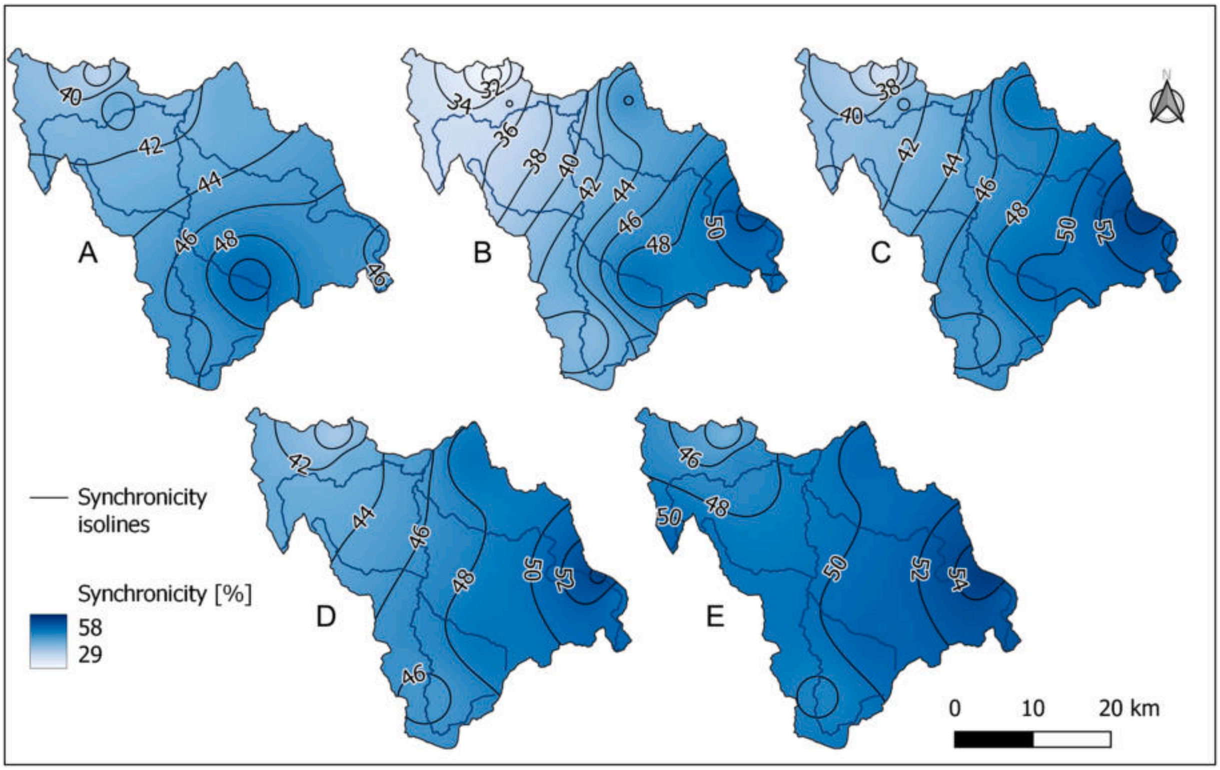

Fig. 9. Synchronicity of flood wave volume in Kłodzko ($FWV_{90\%-K}$) and cumulative rainfall from 24 to 120 h before flood event: (A) CR_{24}, (B) CR_{48}, (C) CR_{72}, (D) CR_{96} and (E) CR_{120}.

responsible for FWV in Kłodzko, whereas the 2–3-day CR are responsible for FPQ in Kłodzko (compare Figs. 7 with 9), (6) rainfall recorded in the east and south-east side of the upper NKR catchment is more responsible for flood wave size in Kłodzko than rainfall recorded in the west side (Figs. 7 and 9), (7) in the Biała Lądecka River sub-catchment, closed by gauge Żelazno, generally the highest synchronicities of CR with FPQ_{SC} and $FWV_{90\%\text{-}SC}$ were recorded (Figs. 6 and 8), (8) the case of a pair of stations Międzylesie (river gauge) - Międzylesie (rainfall station) draws special attention since not every rainfall station reflects well the rainfall conditions in a given sub-catchment area (Fig. 6).

The rainfall-driven floods, especially if they occur over a larger area, are caused by specific synoptic conditions. Bednorz et al. (2019) identified 17 floods, which covered entire Sudety Mountains and designated five types of synoptic patterns causing them. The maximum rainfall during these events was recorded four times at meteorological station Nowy Gierałtów, located in the Biała Lądecka River catchment, what proves the flood-potential character of this NKR tributary. The authors concluded, that in the majority of the Sudety Mountains rivers, the maximum recorded runoff followed immediately (usually with an about one-day delay) extremely high precipitation over this area. Results of the research indicate that this dependency in the upper NKR catchment may be more complex, especially if different flood parameters (peak flow and volume) and cumulative rainfall sums are considered.

It should be emphasized, as it is has been confirmed by the United Nations Office for Disaster Risk Reduction, that risk is complex (UNDRR, 2019). The proposed methodology considers one type of geohazards (however, it compiles multiple variables describing floods and flood-causing rainfall), but there is serious need for development of multi-hazard assessment methodologies, because hazardous events are sometimes difficult to be isolated precisely, or one hazardous event can also trigger another (referred to as a 'compound hazard') (UNDRR, 2020). Moreover, it is widely recognized that hazards can often combine to worsen their joint impact, but there are proofs that they can also tend to be mutually exclusive (at seasonal timescales), and ignoring it overestimates worst-case risk (Hillier et al., 2020). There is a considerable potential in using copulas in such a multi-hazard assessment, through setting up a multi-variate copula-based model to assess the dependencies between given hazards and estimate compound hazard – attempts have been made in that field (e.g. Sadegh et al., 2018, Ganguli et al., 2020, Fan et al., 2021, He et al., 2022, Karatzetzou et al., 2022, Ming et al., 2022).

In the research, similarly to e.g. Rahimi et al. (2021), the threshold-based approach for flood event selection was used. Rahimi et al. (2021) investigated dependencies between the flood event variables (FPQ, FWV and FWD), using both data-based and model-based analyses – it was found e.g., that the FPQ-FWV dependence was greater than the FPQ-FWD and FWV-FWD dependencies. In the presented case study the synchronicity of FPQ and FWV in two variants (total FWV and FWV overreaching 90th percentile) was calculated, what allowed to conclude that FPQ had a stronger relationship with volume of the "top" of the flood waves than with its total volume. Although there are differences in methodologies and used data, this conclusion may bring some new insights into results of Brunner et al. (2018), who investigated impact of climate change on floods in a bivariate context and found that peak discharges and hydrograph volumes were not necessarily equally affected by the projected climate change. The bivariate analysis conducted by Xu et al. (2017) also found that the flood peak was highly correlated with flood volume.

Blöschl et al. (2020), as mentioned in Introduction, indicated that an important component of flood-risk assessment tools would be models that capture, among others, rainfall-runoff transformation on the land surface, including the role of precipitation and seasonality in flood generation. The results and formulated dependencies and rules proved the usefulness of the proposed method for flood hazard assessment, even for an area with complex environmental and hydrological conditions such as the upper NKR catchment. It is important to analyse a hazard in a broader context, considering the mechanisms of the hazardous process on the one side, and potential implications of the threat occurrence (for humans, societies, infrastructure, environment etc.) in a following risk assessment on the other side. It is the issue raised by other researchers, e.g. Ozga-Zielinski et al. (2018) who indicated a different perspective on the evaluation of hazard, risk and reliability of the hydrological system in terms of floods. Going one step further, beyond assessment of vulnerability, hazard, risk etc., we should point at the issue of proper flood risk governance, raised e.g. by Hegger et al. (2016) and Matczak, Hegger (2021), because even the most comprehensive flood risk evaluation cannot replace strategic planning and dealing with that issue in reasonable and structured manner. In Poland, as emphasized by Wyżga et al. (2018), a change in the long-established paradigm is needed to decelerate flood runoff and increase floodwater retention in undeveloped parts of the valleys, with the benefit of reduced flood hazard in urbanized areas.

The research contributes to solving the issues connected with flood modelling of concentric rivers systems in mountainous areas, such as the upper NKR catchment. The main issue in this matter is the coincidence of flood waves occurrence on the main water course and its tributaries (Li et al., 2022). Basing on solutions like the proposed methodology, considering flood event and causing it rainfall, there is no need to rely only on historical (empirical) floods coincident events, but there is a potential of probabilistic forecast, telling which precipitation situations can turn into significant flood event in the given catchment and how the flood wave can influence the main river. In this matter, potentially important can be the "high asynchronicity" measure (sectors 3 and 7, see Fig. 4 and Table 4), because it presents the probability of occurrence of situations, which can be missed by early warning systems or within standard flood hazard modelling, like relatively small precipitation causing dangerous flood event.

The proposed methodology, however, has also some limitations. It is dependent on flow and rainfall data availability, both in spatial (e.g., meteorological stations records have to properly represent precipitation conditions in a given catchment) and temporal terms. The case study was conducted based on daily flow and rainfall data, but theoretically the results could be more detailed and adequate for the mountainous area, if the data with higher time resolution were used (e.g., on the basis of the 12-hour intervals).

Cumulating daily rainfall sums, counting from the flood event occurrence date backwards, limits the usefulness of the methodology for forecasting purposes, because the flood occurrence date must be known to start the analysis. The methodology considers only summer (rainfall-driven) floods, but serious problem of the mountainous areas are also snowmelt floods, which must be taken into account to perform a complete flood hazard assessment. Another issue is an underlying uncertainty of results obtained with the use of the copula-based models, as indicated e.g. by Zhang et al. (2021), Fan et al. (2021) and Tootoonchi et al. (2022). These limitations, however, do not jeopardise the usefulness of the methodology and obtained results, but they have to be taken into account and considered every time when the introduced method is going to be applied.

The proposed methodology should be also developed in terms of the climate change, because of its undoubted impact on hydrological processes, also in terms of the considered upper NKR catchment. Pińskwar et al. (2018) indicate an increase of daily maximum precipitation, both for winter and summer half-years. According to Piniewski et al. (2017), river floods in NKR catchment are projected to increase, too. The development of the methodology can be based on e.g. stochastic weather generators (Paschalis et al., 2013; Peleg et al., 2017) to assess flood hazard in terms of future climate conditions. Some successful cases of combining of weather generators and copulas are presented for instance by Li and Babovic (2019a) (2019b). Another issue is a direct human impact in the upper NKR catchment. The mentioned earlier on-going construction of dry reservoirs will influence future flood hazard of the region, and the presented results may be helpful in setting water management instructions or assessment of their effectiveness.

The introduced flood hazard assessment can be used as part of the following flood risk assessment. Future development of the proposed methodology should also consider spring (snowmelt) floods and their relationship not only with precipitation, but also with air temperatures. It should also address the problem of uncertainty estimation. It can also be adapted for forecasting purposes, to provide the greater usefulness for emergency management and early warning. The development potential lies also in using the multivariate (instead of bivariate) approach, as e.g. You et al. (2019).

To sum up, the proposed methodology allows to assess the spatio-temporal dependencies between the most important flood characteristics and flood-causing rainfall, and on that basis draw conclusions regarding the hazard of summer floods. In the results assessment, to formulate general spatio-temporal regularities for the studied area, attention should be paid particularly to: (1) in which CR variant the synchronicity is the highest and when it drops down, (2) value of the highest and the lowest synchronicity, (3) location of the gauges / stations in relation to each other (e.g., to assess if the meteorological station represents well the rainfall conditions in a given catchment), and (4) the geographical position (e.g., altitude) of gauges / stations that show similar dependencies.

CRediT authorship contribution statement

Adam Perz: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing. **Dariusz Wrzesiński:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Supervision, Validation, Writing - original draft, Writing - review & editing. **Leszek Sobkowiak:** Investigation, Methodology, Validation, Writing - original draft, Writing - review & editing. **Radosław Stodolak:** Investigation, Validation, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Acknowledgements

The research was carried out under the "GEO-INTER-APLIKACJE" project (No. POWR.03.02.00–00-I027/17) and under the internal faculty research grant, both implemented at the Faculty of Geographical and Geological Sciences of Adam Mickiewicz University in Poznań, Poland. Adam Perz is a scholarship holder of the Adam Mickiewicz University Foundation for the academic year 2021/2022.

Appendix A

See Table A1.

Table A1
Synchronicity of cumulative rainfall (CR) and flood peak flow (FPQ).

Rain gauge station	P-24				P-48				P-72				P-96				P-120			
	Syn.	Asyn.			Syn.	Asyn.			Syn.	Asyn.			Syn.	Asyn.			Syn.	Asyn.		
		T	MAs	HAs		T	MAs	HAs		T	MAs	HAs		T	MAs	HAs		T	MAs	HAs
Nysa Kłodzka River – river gauge Międzylesie																				
Międzylesie	32.5	67.5	37.8	29.7	42.0	58.0	36.7	21.3	49.2	50.8	35.3	15.5	48.7	51.3	35.2	16.1	48.0	52.0	35.6	16.4
Nysa Kłodzka River – river gauge Bystrzyca Kłodzka II																				
Międzylesie	41.0	59.0	37.5	21.5	48.3	51.7	35.5	16.2	52.4	47.6	33.5	14.2	50.7	49.3	34.3	15.0	51.0	49.0	35.1	13.9
Międzygórze	44.2	55.8	36.4	19.4	57.4	42.6	32.7	9.9	56.0	44.0	33.7	10.4	55.4	44.6	33.4	11.2	56.3	43.7	33.5	10.2
Nysa Kłodzka River – river gauge Kłodzko																				
Międzylesie	40.3	59.7	37.5	22.2	44.5	55.5	35.9	19.6	50.0	50.0	35.0	15.0	47.3	52.7	34.9	17.8	48.9	51.1	35.1	16.0
Międzygórze	46.1	53.9	37.5	16.4	51.3	48.7	35.6	13.2	51.4	48.6	34.9	13.7	49.5	50.5	35.5	14.9	50.8	49.2	35.0	14.2
Bielice	44.0	56.0	37.3	18.7	51.0	49.0	35.2	13.8	51.0	49.0	34.5	14.5	49.1	50.9	35.6	15.3	49.9	50.1	34.4	15.7
N. Gierałtów	40.8	59.2	36.9	22.3	57.3	42.7	33.6	9.1	55.1	44.9	33.9	11.0	51.0	49.0	34.6	14.3	51.9	48.1	34.6	13.4
Zieleniec	39.4	60.6	36.6	24.0	41.7	58.3	37.4	20.9	44.5	55.5	37.0	18.5	44.9	55.1	36.5	18.6	50.6	49.4	34.6	14.8
Chocieszów	36.7	63.3	37.3	26.0	35.6	64.4	37.3	27.1	39.7	60.3	36.7	23.6	42.1	57.9	36.4	21.5	44.2	55.8	36.7	19.1
Polanica-Z.	42.5	57.5	36.1	21.4	43.2	56.8	36.8	20.0	47.1	52.9	36.5	16.4	48.1	51.9	36.5	15.4	49.6	50.4	35.5	15.0
Podzamek	39.1	60.9	36.6	24.3	51.0	49.0	35.2	13.8	53.4	46.6	34.1	12.5	53.5	46.5	34.3	12.2	53.4	46.6	33.7	12.9
Kłodzko	39.5	60.5	37.7	22.8	42.1	57.9	36.4	21.5	46.7	53.3	35.9	17.4	48.5	51.5	35.1	16.4	50.7	49.3	34.5	14.8
Biała Lądecka River – river gauge Lądek Zdrój																				
Bielice	51.6	48.4	35.9	12.5	56.9	43.1	34.3	8.8	59.2	40.8	32.3	8.8	61.3	38.7	32.0	6.6	66.3	33.7	28.5	5.2
N. Gierałtów	54.9	45.1	33.9	11.2	56.9	43.1	32.7	10.4	58.8	41.2	32.4	8.8	64.5	35.5	30.3	5.2	63.9	36.1	30.3	5.8
Biała Lądecka River – river gauge Żelazno																				
Bielice	41.8	58.2	36.0	22.2	56.8	43.2	33.4	9.8	62.4	37.6	31.6	6.0	64.7	35.3	30.2	5.1	64.7	35.3	29.8	5.5
N. Gierałtów	42.4	57.6	37.8	19.8	59.1	40.9	32.5	8.4	71.8	28.2	25.7	2.5	72.6	27.4	25.3	2.1	69.1	30.9	27.8	3.2
Bystrzyca Dusznicka River – river gauge Szalejów Dolny																				
Zieleniec	42.2	57.8	36.7	21.1	53.7	46.3	34.6	11.7	50.7	49.3	35.9	13.4	51.0	49.0	34.1	14.9	48.3	51.7	36.3	15.4
Chocieszów	45.2	54.8	36.3	18.5	53.8	46.2	34.6	11.6	58.5	41.5	32.5	9.0	55.3	44.7	33.6	11.1	54.8	45.2	33.6	11.6
Polanica-Z.	45.5	54.5	35.5	19.0	57.1	42.9	32.9	10.0	61.8	38.2	31.4	6.8	58.6	41.4	32.4	9.0	54.9	45.1	33.6	11.5

MAs – moderate asynchronicity, HAs – high asynchronicity

Appendix B

See Table B1.

Table B1
Synchronicity of cumulative rainfall (CR) and flood wave volume ($FWV_{90\%}$).

Rain gauge station	P-24				P-48				P-72				P-96				P-120			
	Syn.	Asyn.			Syn.	Asyn.			Syn.	Asyn.			Syn.	Asyn.			Syn.	Asyn.		
		T	MAs	HAs		T	MAs	HAs		T	MAs	HAs		T	MAs	HAs		T	MAs	HAs
Nysa Kłodzka River – river gauge Międzylesie																				
Międzylesie	31.5	68.5	37.6	30.9	37.0	63.0	36.8	26.2	43.9	56.1	36.4	19.8	40.7	59.3	36.9	22.5	41.7	58.3	35.7	22.5
Nysa Kłodzka River – river gauge Bystrzyca Kłodzka II																				
Międzylesie	39.8	60.2	36.1	24.1	41.7	58.3	36.0	22.3	48.9	51.1	35.7	15.4	51.3	48.7	34.7	14.0	51.2	48.8	33.9	14.9
Międzygórze	43.1	56.9	37.1	19.8	46.5	53.5	36.0	17.4	49.1	50.9	35.2	15.7	51.8	48.2	34.5	13.7	51.3	48.7	34.7	14.0
Nysa Kłodzka River – river gauge Kłodzko																				
Międzylesie	45.8	54.2	35.6	18.6	41.1	58.9	37.5	21.4	45.6	54.4	36.4	18.1	45.6	54.4	35.7	18.7	47.7	52.3	35.5	16.8
Międzygórze	50.9	49.1	35.1	14.0	49.6	50.4	36.3	14.1	50.5	49.5	34.5	14.9	49.3	50.7	34.5	16.2	51.4	48.6	35.0	13.5
Bielice	45.8	54.2	36.6	17.5	50.2	49.8	34.6	15.2	51.8	48.2	35.0	13.2	50.2	49.8	36.0	13.9	52.1	47.9	34.8	13.1
N. Gierałtów	46.4	53.6	36.3	17.3	52.8	47.2	33.6	13.6	55.2	44.8	33.0	11.7	54.3	45.7	34.3	11.4	55.7	44.3	33.5	10.8
Zieleniec	42.1	57.9	35.6	22.3	34.2	65.8	36.5	29.3	39.8	60.2	37.8	22.4	43.2	56.8	36.3	20.5	50.7	49.3	35.1	14.2
Chocieszów	37.1	62.9	38.1	24.9	29.2	70.8	37.5	33.3	34.4	65.6	37.9	27.7	38.5	61.5	37.3	24.2	42.5	57.5	36.8	20.6
Polanica-Z.	42.9	57.1	37.4	19.6	36.0	64.0	37.2	26.8	42.2	57.8	37.5	20.3	43.3	56.7	38.4	18.3	47.5	52.5	36.2	16.3
Podzamek	43.1	56.9	36.6	20.3	46.1	53.9	36.9	17.1	49.1	50.9	36.0	14.9	49.7	50.3	35.6	14.7	50.8	49.2	34.8	14.5
Kłodzko	40.8	59.2	37.1	22.1	38.5	61.5	36.8	24.7	43.8	56.2	36.7	19.5	45.0	55.0	36.9	18.1	48.5	51.5	35.7	15.8
Biała Lądecka River – river gauge Lądek Zdrój																				
Bielice	45.0	55.0	36.7	18.4	44.8	55.2	35.8	19.4	46.6	53.4	35.0	18.4	49.2	50.8	35.0	15.8	51.9	48.1	34.7	13.4
N. Gierałtów	40.7	59.3	37.2	22.1	41.2	58.8	38.0	20.8	44.8	55.2	36.8	18.4	47.3	52.7	35.5	17.2	51.0	49.0	34.5	14.5
Biała Lądecka River – river gauge Żelazno																				
Bielice	36.6	63.4	36.7	26.7	44.3	55.7	37.4	18.3	52.1	47.9	34.6	13.2	56.0	44.0	33.0	11.1	55.0	45.0	33.3	11.7
N. Gierałtów	37.7	62.3	37.2	25.0	49.5	50.5	35.3	15.3	59.2	40.8	32.2	8.7	59.4	40.6	32.3	8.2	57.0	43.0	33.7	9.2
Bystrzyca Dusznicka River – river gauge Szalejów Dolny																				
Zieleniec	43.8	56.2	36.3	19.9	43.9	56.1	35.7	20.5	46.2	53.8	35.9	17.9	46.3	53.7	35.6	18.1	47.1	52.9	36.0	17.0
Chocieszów	51.3	48.7	35.3	13.4	45.2	54.8	36.6	18.2	47.4	52.6	35.9	16.7	45.1	54.9	38.3	16.7	47.6	52.4	37.1	15.3
Polanica-Z.	50.2	49.8	34.8	15.0	47.9	52.1	35.5	16.6	50.8	49.2	35.3	13.9	49.0	51.0	35.6	15.4	49.6	50.4	34.8	15.6

MAs – moderate asynchronicity, HAs – high asynchronicity

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2022.101214. These data include Google maps of the most important areas described in this article.

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water

Article

Flood-Triggering Rainfall and Potential Losses—The Copula-Based Approach on the Example of the Upper Nysa Kłodzka River

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Abstract: Floods are natural phenomena, inextricably related to river regimes, which can threaten human health and life, the environment, cultural heritage, economic activity and infrastructure. The aim of the research is to assess the connection between rainfall and river flood risk. The proposed methodology is presented on the example of the upper Nysa Kłodzka River (NKR) catchment and Kłodzko town located on NKR, which are two of the most flood-prone areas in the Odra River basin. The methodology is based on the well-established methods of potential flood losses (PFL) estimation and the copula-based model, allowing an assessment of connections between rainfall and flood losses in a probabilistic way. The results are presented using the 'synchronicity' measure. Seventeen significant summer (rainfall-driven) flood waves were selected, for which PFL were estimated and cumulative rainfall was calculated for 24, 48, 72, 96 and 120 h preceding the flood peak. It was found that the synchronicity of PFL and the 24 h rainfall was the lowest among the analyzed variants, while for the 48 to 120 h rainfall the highest synchronicity was identified at precipitation gauge Podzamek.

Keywords: flood risk; rainfall; potential flood losses; copula; synchronicity; Poland; Nysa Kłodzka River

Citation: Perz, A.; Wrzesiński, D.; Budner, W.W.; Sobkowiak, L. Flood-Triggering Rainfall and Potential Losses—The Copula-Based Approach on the Example of the Upper Nysa Kłodzka River. *Water* **2023**, *15*, 1958. https://doi.org/10.3390/w15101958

Academic Editor: Marco Franchini

Received: 18 April 2023
Revised: 13 May 2023
Accepted: 19 May 2023
Published: 22 May 2023

1. Introduction

Floods are natural phenomena inextricably related to river regimes. In general, they are responses to increased water supply due to precipitation or snow and ice melts. Floods play a significant role in environment functioning; they are even essential for certain ecosystems. For centuries, floodplains and river valleys were also chosen by humans to build their settlements due to their water-resources availability, fertile soil, and relatively flat terrain, or for military purposes. However, sometimes, proximity to rivers turns from a blessing into a curse, because floods can be of extreme proportions and be catastrophic in their consequences. They can threaten human health and life, the environment, cultural heritage, economic activity and infrastructure [1,2]. Extreme floods cannot be avoided; thus, the risk of their occurrence should be a part of rational water management and governance [3,4], especially in the context of climate change [5].

What is more, recent times can be taken as an exceptionally flood-rich period in terms of the timing of flood occurrences, their magnitudes and their spatial extent in Europe [6,7]. For last 150 years in Europe, there has been an increase in the area inundated by floods; however, this has been accompanied by a relative (to the demographic and economic growth) reduction in fatalities and economic losses [8]. There is evidence that climate change will make extreme hydrological events in Europe more frequent and adverse [9–14], although these changes will not occur in a similar way in every region [15–22]. In general, global warming is going to significantly increase human and economic losses from river flooding in the future [23–26]. However, the changing climate is not the only driver of increasing flood risk—there is a constant pressure to convert floodplains into artificial surfaces [27,28], and intensive land use also increases the exposure of human assets to floods [29].

In such conditions, the significance of a proper flood hazard and risk assessment is growing. Floods, in water management and governance, may be considered using several terms, including sensitivity (or susceptibility), exposure, vulnerability, resilience, hazard and risk. Some of them are sometimes treated as synonyms, which leads to misunderstandings. In this paper, the terms "hazard" and "risk" are understood in line with the Floods Directive [1]—"hazard" is connected to the occurrence probability of a flood event, while "risk" is a combination of hazard and the potential adverse consequences associated with a flood event. According to these definitions, in the standard flood risk assessment approach, two things are crucial: calculation of probable values of river flows/water levels (leading to the designation of the inundation zones and flood water depths), and an estimation of potential flood losses (PFL).

Such an approach meets certain obstacles [30], which leads to the uncertainty of results [31]; thus, risk-assessment methods are developed, e.g., by applying the theory of reliability [32], the rapid flood risk assessment based on issued predictions [33] or a continuous approach which allows for the modelling and simulation of spatially and temporally correlated hazard scenarios at a weekly time scale [30]. A growing number of methods are based on copulas [24,30,34] or machine-learning techniques [35,36]. These methods allow for the estimation of the PFL and flood risk; however, it should be remembered that these analyses should be a part of flood risk management and should be followed by, e.g., preparing spatial development policies and establishing investment priorities in flood protection infrastructure. This is usually carried out using economic methods, such as a cost–benefit analysis (CBA) [37–39].

Many researchers also focus on pluvial flood hazard and risk (e.g., [40–42]), especially in urban areas (e.g., [43–45]). However, such studies, in most cases, develop modelling methods and tools (in terms of rainfall-runoff relation, losses, etc.), rather than searching for spatial dependencies between economically estimated flood risk and the factors causing it in the catchment, such as rainfall or snowmelt; such studies have been performed, e.g., by [46,47].

This research aims to fill the existing research gap by assessing the connection between rainfall and river flood risk. The presented methodology is based on the well-established methods of PFL estimation and the copula-based 'synchronicity' measure. It is demonstrated on the example of Kłodzko town, Poland, located in the Nysa Kłodzka River (NKR) catchment.

The research fits into the trend of analyzing relationships between hydro- and meteorological variables in terms of synchronicity and asynchronicity, described also as, e.g., "synchronous–asynchronous encounter probability", "probability of synchronous or asynchronous occurrence", or "dryness–wetness/rich–poor encounter probability". Such an approach has been used in the analyses of the probability of the co-occurrence of precipitation [48–50], runoff and sediment load [51–53], the water level of a sea and coastal lakes [54], maximum or average annual discharge/runoff [55–59], precipitation and runoff [60–62], flood hazard [62] or water transfer projects [63]. The novelty of this research is its combining of the estimated economic flood losses and rainfall data within one copula-based model, which allows the formulation of spatio-temporal dependencies.

2. Study Area, Materials and Methods

2.1. Study Area

The upper NKR catchment lies in the Polish part of the Sudety Mountains (Figure 1). It is one of the areas most threatened by flooding in Poland [64], and rivers flowing from there to the Odra River have one of the highest values of the flood potential index in the country [65,66]. They are also characterized by apparent differences in terms of the uncertainty and stability of the river runoff regime [67]. Devastating floods in that region have been documented from as early as in the 14th century, when the July 1310 flood killed more than 1500 people [68]. One of the worst natural disasters in the modern history of Poland—the July 1997 flood in the Odra River basin—also originated from the upper NKR catchment. It is called the "Millennium Flood", and this term is still rhetorically used to describe an event whose scale exceeded all imagination of the possible disaster size [69], because it caused more than 50 fatalities and losses counted in billions of USD. The July 1997 flood also hit the town of Kłodzko, killing several inhabitants and depriving more than 500 families of virtually everything they owned [69].

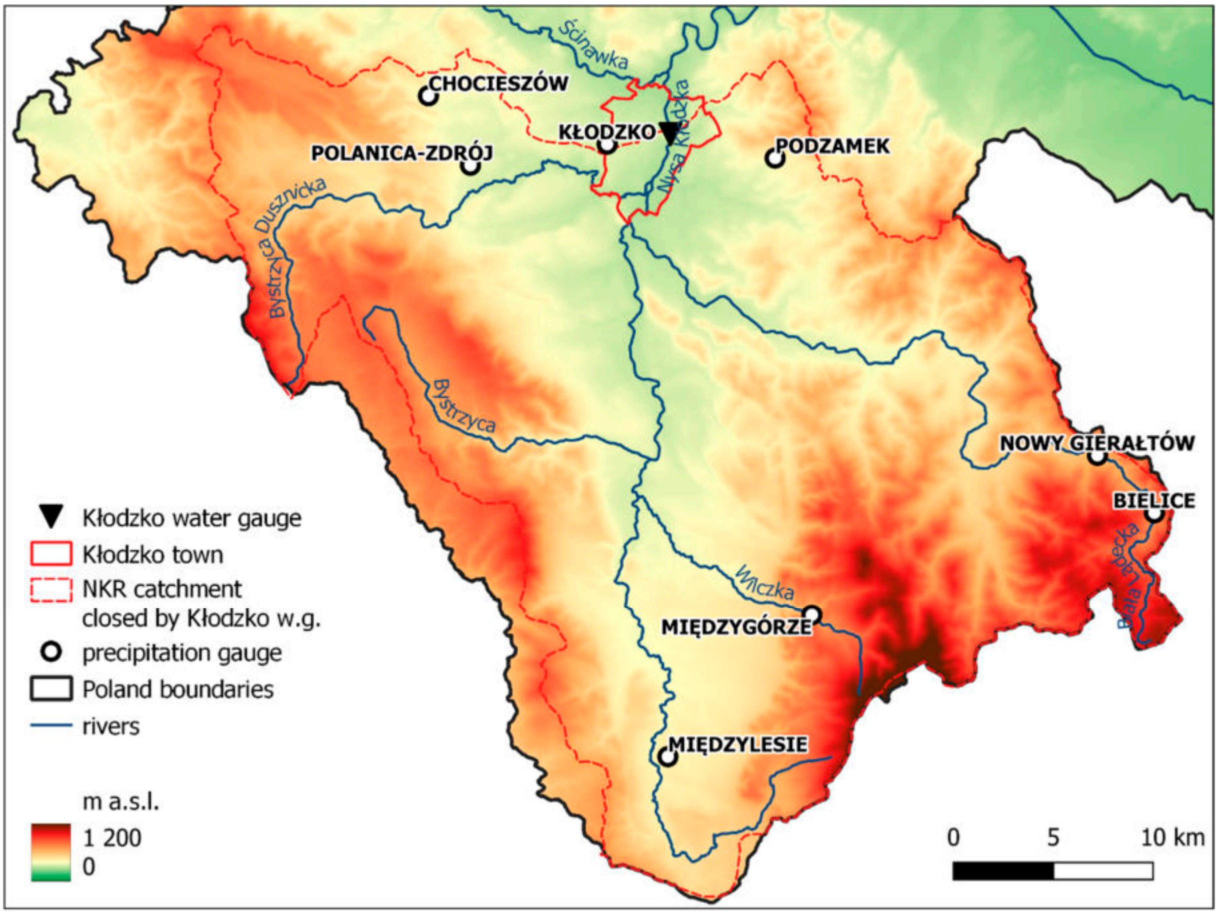

Figure 1. Study area—location of Kłodzko town, upper NKR catchment and precipitation gauges.

The possibility of flood-wave coincidence on the NKR and the Odra River is recognized as one of the serious environmental hazards in Poland [68,70]. The concentric arrangement of the river network and river-beds deposition in older formations are highlighted by [71] as favorable conditions for the formation of flood waves in that area. In their research, Bednorz et al. [71] determined five patterns of cyclonic circulation characterized by different intensities, extents and origins, which are responsible for heavy rainfall triggering floods in the Sudety Mountains. Kłodzko town was established as one of municipalities with the highest flood risk levels (according to the Flood Risk Management Plans) in the entire NKR catchment [72]. At the same time, the adaptability level of the town was assessed as one of the highest in that region, too.

Kłodzko town is located on the NKR, it has 25,239 inhabitants (as of 31 June 2022) [73] and an area of 24.84 km^2. Due to the location in the river valley, its elevation is differentiated, ranging from 280 to 431 m a.s.l. A detailed description of the upper NKR catchment, including precipitation and hydrological conditions, is given in [74] and in earlier papers—please refer to [60–62,75].

2.2. Data

The study was conducted on the basis of values of daily water levels (H) of the NKR in Kłodzko town and rainfall (R) recorded in precipitation gauges in the NKR catchment. The data were obtained from the resources of the Institute of Meteorology and Water Management—National Research Institute in Warsaw, Poland, and downloaded using the climate R package [76]. The data cover the period of hydrological years (from 1 November to 31 October) 1971–2021.

In the proposed methodology, the digital elevation model (DEM) was used, with resolution of 1 m × 1 m. The Topographic Objects Database (BDOT10k) was used in estimation of flood losses, based on the land use classification. Both DEM and BDOT10k are provided by the Head Office of Geodesy and Cartography in Warsaw, Poland.

The obtained data sets are complete and sufficient to carry out the study and draw reliable conclusions.

2.3. Methods

2.3.1. Selection of Significant Floods and Rainfall Data Preparation

Firstly, based on the obtained data, the average annual maximum water level (hereinafter referred to as "mean high water"—MHW) was calculated. This value was applied to designate significant summer (rainfall-driven) floods—every flood equal to or higher than MHW was taken into the analyses. Exceedance of MHW for several following days was treated as one flood event, and for the further analyses only peak water levels were selected.

Besides the empirical H, the probable water levels were also obtained from the available flood hazard maps [77], for return periods of 10, 100 and 500 years, respectively. In order to obtain the flooding surface elevation (FSE, expressed in m a.s.l.), used to estimation of flood inundation zones (FIZ) and floodwater depths (FWD), all selected H were added to the "zero" level of the river gauge.

For each selected flood event, the rainfall from five preceding days was identified and summed to the 24 h (R_{24}), 48 h (R_{48}), 72 h (R_{72}), 96 h (R_{96}) and 120 h (R_{120}) rainfall.

2.3.2. Estimation of FIZ Range

To obtain FIZ for each selected H, without using the complex hydrological/hydraulic model, the following steps were carried out using the GIS software (a visualization of these steps is presented in Figure 2):

1. The river-valley and river-bed cross-sections were drawn (for NKR and its tributaries within the Kłodzko town boundaries).
2. For each cross-section, elevation of the riverbank from DEM was added.
3. For Kłodzko water-gauge cross-section, values of H were added.
4. The differences between Kłodzko water-gauge elevation and elevations of other cross-sections were calculated.
5. FSE in each cross-section (FSE_{CS}) was calculated with the use of formula (Equation (1)):

$$FSE_{CS} = H + d \tag{1}$$

   where d—difference between elevation of the water-gauge cross-section and the given cross-section ("+" for cross-sections upstream, "−" for cross-sections downstream).
6. To obtain FIZ, the triangulated irregular network (TIN) model was applied to interpolate floodwater surface for each H.
7. TIN was transformed into raster, and DEM was subtracted from it.
8. The obtained raster was reclassified according to four depth classes (see Section 2.3.3 for details).
9. The reclassified raster was transformed into polygon layer presenting initial FIZ range and FWD.
10. The range of initial FIZ was limited to the administrative boundaries of the Kłodzko town.

11. The final FIZ was obtained by subtracting the FIZ parts not linked to the river (e.g., behind dikes or naturally lower than the river) and riverbeds area from the polygon layer.

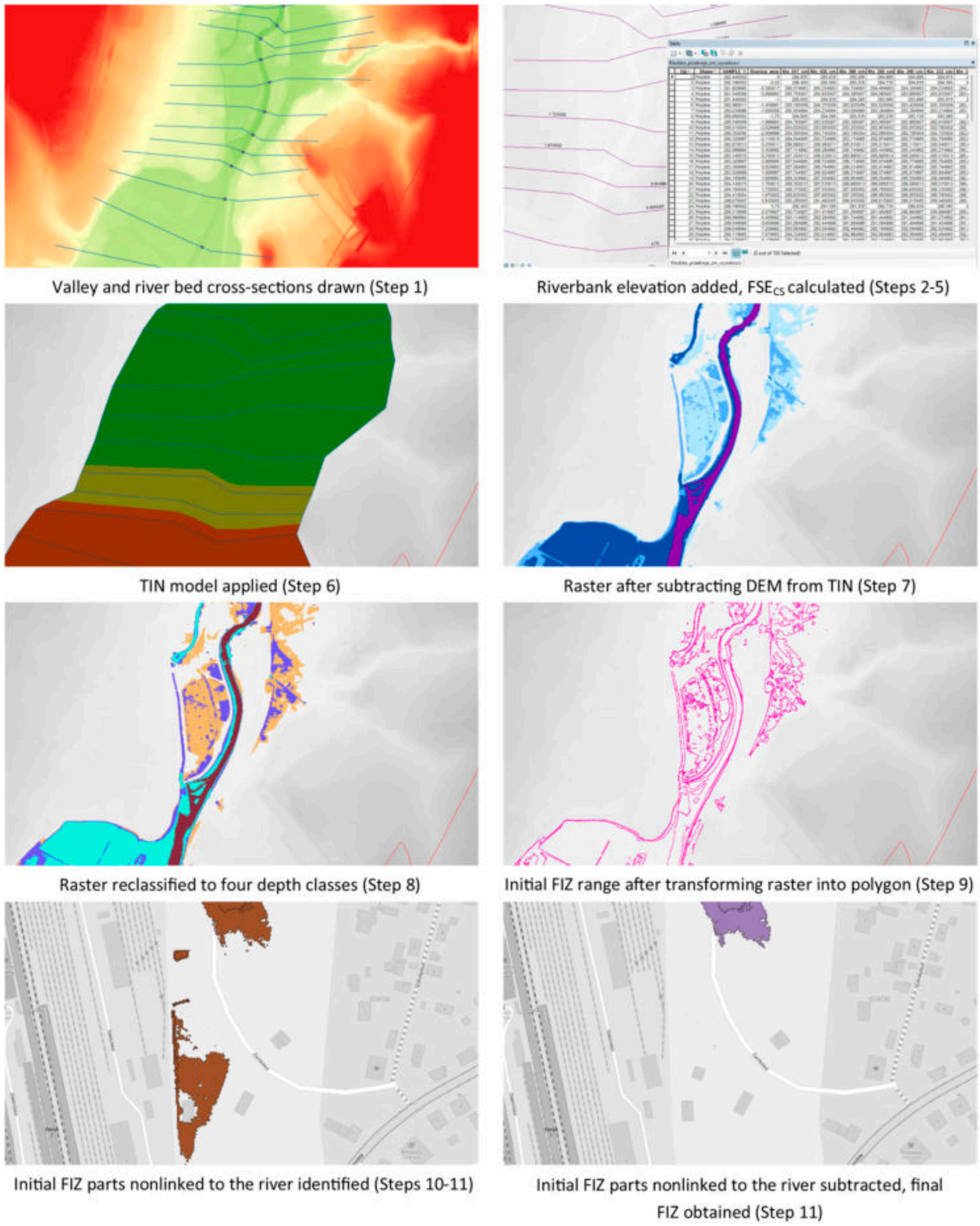

Figure 2. Visualization of steps in obtaining the final FIZ range.

2.3.3. Estimation of PFL

For each final FIZ, PFL were estimated on the basis of land use type in accordance with the methodology used in preparation of the updated flood risk maps [78] and the updated flood risk management plans for the Odra River basin [79]. The approach is based on the methodology for determining the property value indicators proposed by [80]. The property value indicators adopted in the research were indexed using the growth in the economic indicators from 2016 to 2019 [79].

This methodology considers both the types of flooded area (according to BDOT10k) and depth of the water covering it. There are designated eight land use classes and four water depth classes, based on which levels of assets impairment were adopted (Table 1).

Table 1. Property value indicators used in PFL estimation (after [78–80]).

Class No.	Class Name	FWD < 0.5 m	0.5 m < FWD ≤ 2 m	2 m < FWD ≤ 4 m	FWD > 4 m
1	Areas of residential development	20% v	35% v	60% v	95% v
2	Industrial areas	20% v	40% v	60% v	80% v
3	Transportation areas	5% v	10% v	10% v	10% v
4	Forests		0.04 PLN/m^2 (0.01 EUR/m^2)		
5	Recreational and leisure areas		8.81 PLN/m^2 (1.90 EUR/m^2)		
6	Arable land/permanent crops		0.36 PLN/m^2 (0.08 EUR/m^2)		
7	Grassland		0.09 PLN/m^2 (0.02 EUR/m^2)		
8	Other areas and surface waters		-		

Notes: EUR 1 = PLN 4.64 (Polish zloty); v—value of given land use class per m^2 adopted for Lower Silesian Voivodeship: class No. 1—2775.76 PLN/m^2 (598.22 EUR/m^2); class No. 2—1968.34 PLN/m^2 (424.21 EUR/m^2); class No. 3—789.23 PLN/m^2 (170.09 EUR/m^2).

Based on values indicated in Table 1, for each FIZ total PFL was calculated.

2.3.4. Estimation of Distribution Parameters

The best matching statistical distribution type was selected for the analyzed data sets (R and PFL). The log-normal, Gumbel, Gamma and Weibull distributions were taken into consideration. Distribution-parameters estimation was conducted with the help of the maximum-likelihood method. In order to check the goodness of fit of the distribution type in the data series, the Akaike information criterion (AIC) [81] was used (Equation (2)):

$$AIC = N\log\,(MSE) + 2p \tag{2}$$

where MSE—mean square error, N—size of a sample, p—fitted-parameters number or (Equation (3)):

$$AIC = 2\log\,(ML) + 2p \tag{3}$$

where ML—maximum likelihood for model, and p–fitted-parameters number.

The best-fitted distribution type is the one having the lowest value of AIC [81].

2.3.5. Application of Copulas

For H and PFL, the joint distribution was constructed using copulas. A definition of the bivariate Archimedean copula function is as follows (Equation (4)):

$$C_\theta\,(u,v) = \phi^{-1}\,\{\phi(u) + \phi(v)\}, \tag{4}$$

where u and v are marginal distributions, the θ, subscript of copula C, is the parameter hidden in the generating function ϕ, and ϕ is a continuous function called a generator which strictly decreases and is convex from I = [0, 1] to [0, ϕ(0)] [82].

The one-parameter Archimedean copulas (Clayton, Gumbel–Hougaard and Frank copula families) were applied (Table 2).

Table 2. Copula function, parameter space, generating function Φ(t), and functional relationship of Kendall's τθ with a copula parameter for selected single-parameter bivariate Archimedean copulas (following [60,62]).

Copula Family	$C_\theta(u,v)$	Generator $\phi(t)$	Parameter $\theta \in$	Kendall's τ_θ
Clayton	$max\left(\left(u^{-\theta}+v^{-\theta}-1\right)^{-\frac{1}{\theta}},0\right)$	$\frac{1}{\theta}\left(t^{-\theta}-1\right)$	$[-1,\infty)\backslash\{0\}$	$\tau=\theta/(2+\theta)$
Gumbel–Hougaard	$exp\left\{-\left[(-ln\,u)^{\theta}+(-ln\,v)^{\theta}\right]^{\frac{1}{\theta}}\right\}$	$(-\ln t)^{\theta}$	$[1,\infty)$	$(\theta-1)/\theta$
Frank	$\frac{-1}{\theta}ln\left[1+\frac{(e^{-\theta u}-1)(e^{-\theta v}-1)}{e^{-\theta}-1}\right]$	$-ln\frac{e^{-\theta t}-1}{e^{-\theta}-1}$	$(-\infty,\infty)\backslash\{0\}$	$1+4[D_1(\theta)-1]/\theta$

In Table 2, *Dk* (*x*) is Debye function (Equation (5)), for any positive integer k,

$$D_k(x) = \frac{k}{k^x}\int_0^x \frac{t^k}{e^t - 1}dt. \quad (5)$$

AIC was applied in order to check the goodness of fit of the joint distribution.

Based on the estimated parameters of statistical distributions (see Section 2.3.4), for the analyzed data pairs (R—PFL) 5000 hypothetical values were randomly generated. They were used for selection of the best-fitted Archimedean copula family for a given data pair, and, subsequently, for forming of an appropriate copula function. Such a procedure (choosing a proper copula family for each data pair independently) helps to avoid having distorted (or even reverse) results—such a possibility was noted, e.g., in [55]. On the basis of empirical values of R and PFL for particular years and generated points, graphs with return period curves were generated. Next, the generated hypothetical values were analyzed using 62.5% and 37.5% probability levels [51,55]. These levels allowed designation of nine sectors (Table 3), which represent various relation types of analyzed variables probable values.

Table 3. Designation of sectors determining the synchronicity and asynchronicity (after [62], modified).

Sector		Relation Type	X	Y
1	LoR–LoPFL	Synchronicity	$X \leq R_{62.5\%}$	$Y \leq PFL_{62.5\%}$
2	LoR–MePFL	Moderate asynchronicity	$X \leq R_{62.5\%}$	$PFL_{62.5\%} < Y \leq PFL_{37.5\%}$
3	LoR–HiPFL	High asynchronicity	$X \leq R_{62.5\%}$	$Y > PFL_{37.5\%}$
4	MeR–LoPFL	Moderate asynchronicity	$R_{62.5\%} < X \leq R_{37.5\%}$	$Y \leq PFL_{62.5\%}$
5	MeR–MePFL	Synchronicity	$R_{62.5\%} < X \leq R_{37.5\%}$	$PFL_{62.5\%} < Y \leq PFL_{37.5\%}$
6	MeR–HiPFL	Moderate asynchronicity	$R_{62.5\%} < X \leq R_{37.5\%}$	$Y > PFL_{37.5\%}$
7	HiR–LoPFL	High asynchronicity	$X > R_{37.5\%}$	$Y \leq PFL_{62.5\%}$
8	HiR–MePFL	Moderate asynchronicity	$X > R_{37.5\%}$	$PFL_{62.5\%} < Y \leq PFL_{37.5\%}$
9	HiR–HiPFL	Synchronicity	$X > R_{37.5\%}$	$Y > PFL_{37.5\%}$

Notes: where X = x coordinates of generated points; Y = y coordinates of generated points; R62.5%/PFL62.5% = the value of R or PFL with a probability of exceedance of 62.5%; R37.5%/PFL37.5% = the value of R or PFL with a probability of exceedance of 37.5%; Lo = "low", Me = "medium", and Hi = "high"; and R/PFL = variables used in this study, i.e., cumulative rainfall or potential flood losses (see details in Sections 2.3.1 and 2.3.3).

The synchronicity is the percent share of generated points in sectors No. 1, 5, and 9 (Table 3) in the total number of generated points, whereas the asynchronicity is divided into two types:

- Moderate asynchronicity representing "low–medium", "medium–low", "medium–high" and "high–medium" relation types (sectors Nos. 2, 4, 6, 8).
- High asynchronicity, representing "high–low" and "low–high" relation types (sectors No. 3 and 7).

To put it another way, synchronous and asynchronous occurrences probability (i.e., synchronicity and asynchronicity) of the analyzed variables (i.e., R and PFL) were determined with the calculated threshold values of probability ranges:

- LoR/LoPFL describing the probable values with a probability of exceedance >62.5%;
- MeR/MePFL describing the probable values with a probability of exceedance in a range <62.5% and >37.5%;
- HiR/HiPFL describing the probable values with a probability of exceedance <37.5%.

For description of LoR/LoPFL, MeR/MePFL and HiR/HiPFL, see footer of Table 3.

The sum of asynchronicity and synchronicity is 100%. The obtained results concern precipitation gauges in the NKR catchment, so interpolation of results was conducted to analyze spatial dependencies. It was performed using the inverse distance weighted (IDW) method [83].

The synchronous event is, e.g., when both R in Podzamek rainfall gauge and PFL in Kłodzko are in the same probability range. Synchronicity is the probability of occurrence of such a situation.

Similar methods of using the copulas and synchronicity within the upper NKR catchment were applied in earlier studies [60–62]; however, there are tangible differences between the used data, objectives and findings of that research. The first of these studies [60] focuses on relationships between the annual precipitation totals and river annual runoff. In the second study [61], three relation types were analyzed: between (1) precipitation totals recorded in rain gauge stations and average areal precipitation totals for the whole upper NKR catchment, (2) runoff totals recorded in sub-catchments and runoff totals recorded in Kłodzko water gauge and (3) areal precipitation totals for each sub-catchment and runoff from these sub-catchments. The third study [62], in contrast to the previous ones, does not concern water resources, but focuses on summer flood hazard and relations between flood peak flow, flood wave volume and rainfall in days preceding flood events. Present study, as described earlier, also concerns rainfall in days preceding significant summer flood events, but in relation to PFL, i.e., economic values (losses) used in flood risk analyses.

3. Results

3.1. Selected Flood Events

On the basis of MHW for the Kłodzko water gauge on the NKR (242.80 cm), 30 flood events were identified, among which 17 summer (recorded from May to October) floods were selected as significant ones and taken for further analysis (Table 4). The MHW value was similar to the alarm water level set for the Kłodzko water gauge (240 cm). The estimated PFL for the flood events ranges from PLN 12.1 million (EUR 2.61 million) to PLN 361.4 million (EUR 77.89 million), while the FIZ area is from 0.8 to 4.6 km^2 (Table 4). The highest water level was recorded on 8 July 1997 (Figure 3), during so called "Millennium Flood" (see Section 2.1). From 2011 to 2021, no significant summer flood occurred. For every selected event, the 24 to 120 h rainfall sums were calculated for eight precipitation gauges located in the upper NKR catchment (Figure 1).

Table 4. Significant (i.e., exceeding MHW) historical summer flood events in Kłodzko in 1971–2021 with estimated PFL and FIZ area.

No.	Date	H (cm)	Q ($m^3 \cdot s^{-1}$)	PFL (PLN Million (EUR Million)) [1]	Total FIZ Area (km^2)
1	30.05.1971	266	120	13.4 (2.89)	0.9
2	02.07.1975	330	212	53.4 (11.51)	2.3
3	03.08.1977	380	298	99.0 (21.34)	3.5
4	23.08.1977	310	180	38.4 (8.28)	1.6
5	10.07.1980	350	244	68.2 (14.7)	2.8
6	21.07.1980	300	164	31.4 (6.77)	1.5
7	23.10.1981	260	113	12.1 (2.61)	0.8
8	09.08.1985	290	149	25.2 (5.43)	1.3
9	06.09.1987	286	144	23.5 (5.06)	1.2
10	14.05.1996	290	149	25.2 (5.43)	1.3
11	08.07.1997	517	693	361.4 (77.89)	4.6
12	20.07.1997	328	209	52.2 (11.25)	2.2
13	23.07.1998	380	298	99.0 (21.34)	3.5
14	21.07.2001	282	139	21.7 (4.68)	1.2
15	08.08.2006	340	243	61.0 (13.15)	2.5
16	27.06.2009	435	424	164.1 (35.37)	4.1
17	22.07.2011	305	205	34.9 (7.52)	1.6

Note: [1] EUR 1 = PLN 4.64.

The official flood hazard and flood risk maps for NKR were prepared, based on values of probable water level with probabilities of exceedance: 10, 1, and 0.2% [77]. The same values were also used to estimate PFL and FIZ (Table 5).

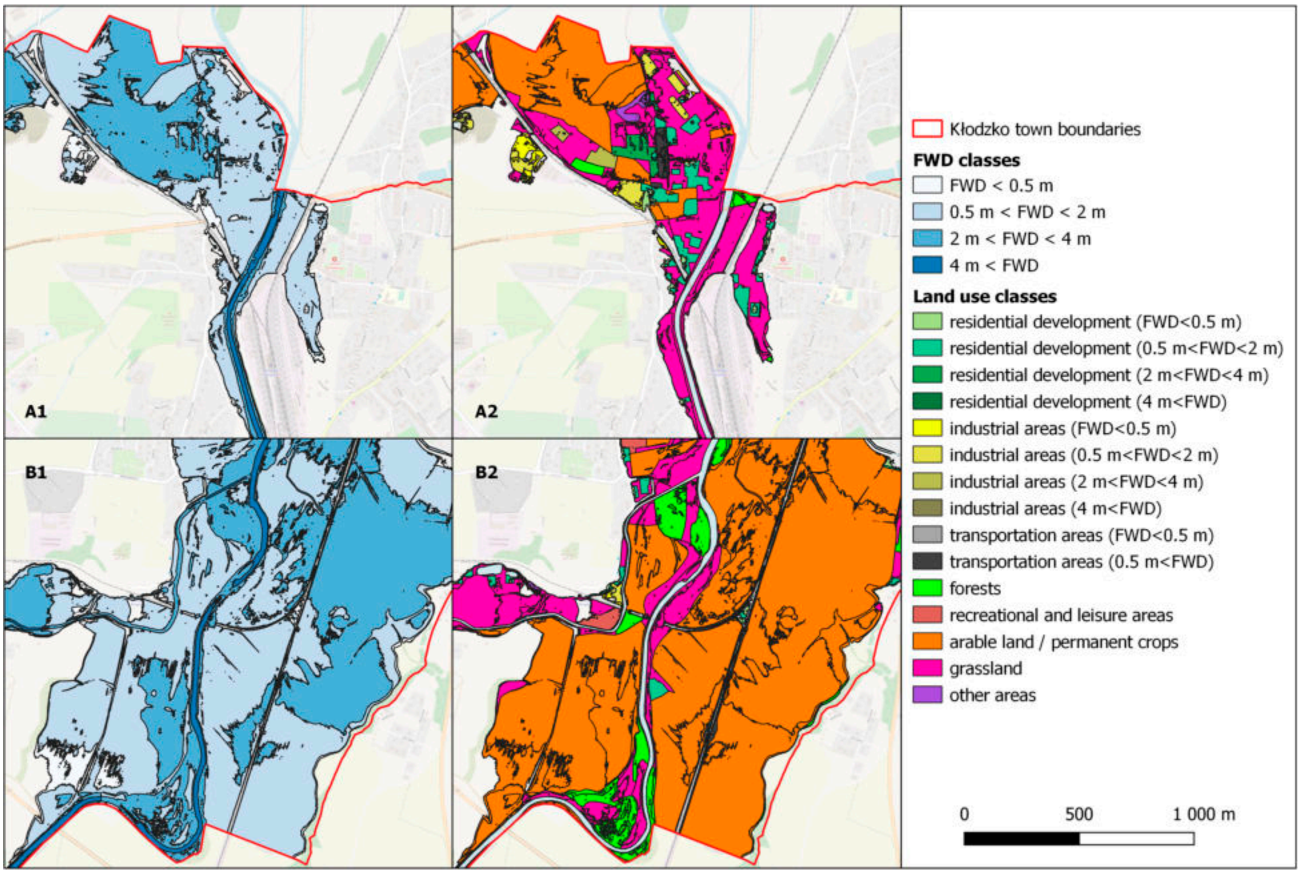

Figure 3. Example of generated FIZ area for flood event of 8 July 1997, with view on the northern (**A1**,**A2**) and southern (**B1**,**B2**) parts of Kłodzko town. FIZ are presented broken down into FWD classes (**A1**,**B1**) and land use classes (**A2**,**B2**) in accordance with the property value indicators used in the PFL estimation (see Table 1 for details).

Table 5. Estimated PFL and FIZ area for floods with a given probability of occurrence in Kłodzko town.

Probability	Return Period	H (cm)	Q ($m^3 \cdot s^{-1}$)	PFL (PLN Million (EUR Million)) [1]	Total FIZ Area (km^2)
10%	10 years	423	391	145.0 (31.25)	3.9
1%	100 years	534	762	408.5 (88.04)	4.7
0.2%	500 years	591	1025	542.6 (116.94)	4.9

Note: [1] EUR 1 = PLN 4.64.

The data comparison shows that in the analyzed period there were only two historical summer flood events exceeding the level of a 10-year flood, while the level of a 100-year flood has never been reached (Figure 4). The PFL value is exponentially rising with water level, while the FIZ area is also rising, but there is an inflection point. These findings will be discussed later.

3.2. Synchronicity of Rainfall and PFL

The probability of the synchronous occurrence of rainfall and PFL in Kłodzko town was calculated for five variants of rainfall sums, from 24 to 120 h (Figure 5A–E). In general, synchronicity between rainfall and PFL is the lowest when R_{24} is considered (Figure 5A), and the longer the aggregation period of rainfall, the higher the synchronicity (Figure 5B–E).

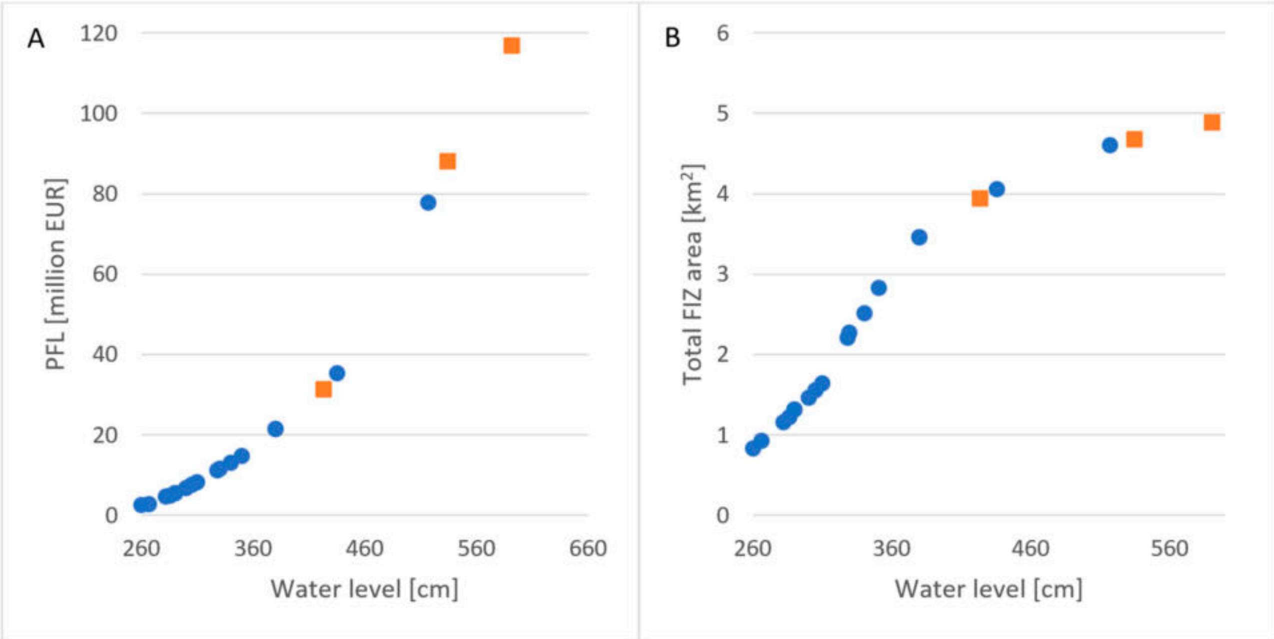

Figure 4. Dependence of water level and estimated PFL (**A**) and total FIZ area (**B**). Blue points refer to significant historical summer floods, orange squares to probable floods.

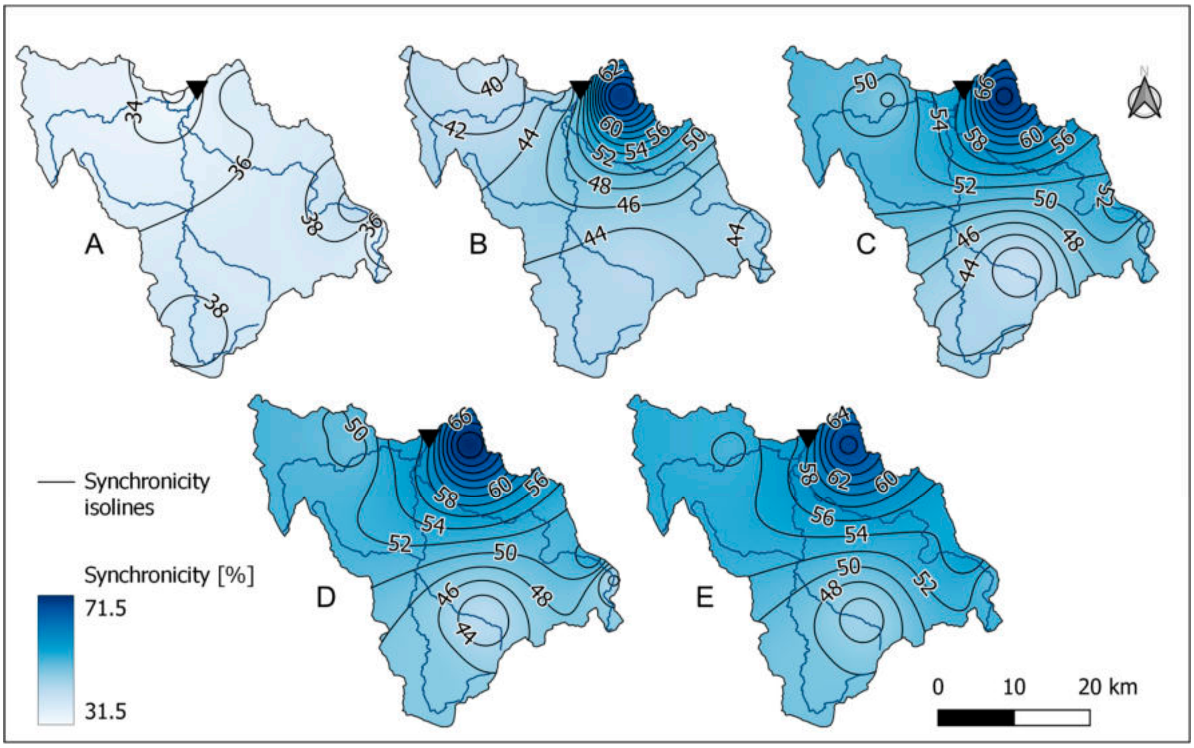

Figure 5. Synchronicity of PFL and cumulative 24 to 120 h rainfall before flood event: (**A**) R_{24}, (**B**) R_{48}, (**C**) R_{72}, (**D**) R_{96} and (**E**) R_{120}.

The synchronicity between R_{24} and PFL (Figure 5A) ranged from 31.6 (Kłodzko) to 41.5% (Nowy Gierałtów), so the relation between PFL and R_{24} is asynchronous. Taking into account that in the analysis the biggest floods are considered, this can be explained by the fact that such events are not usually caused by one-day rainfall. In terms of the relation between R_{48} and PFL (Figure 5B), the highest synchronicity was calculated for the Podzamek precipitation gauge (70%), while for other gauges the synchronicity did not exceed 45%, so it was higher than in the R_{24} variant (Figure 5A); however, the relation was still mostly asynchronous. For data pair R_{72} and PFL (Figure 5C), the synchronicity ranged from 40.3 (Międzygórze) to 70.6% (Podzamek).

The synchronicity is higher than for R_{24} and R_{48} for precipitation gauges located in the Biała Lądecka and Bystrzyca Dusznicka river catchments, but the relation between PFL and rainfall in the upper section of the NKR is asynchronous. For variant R_{96} and PFL (Figure 5D), the synchronicity ranged from 42.4 (Międzygórze) to 71.4% (Podzamek)—the result for the Podzamek precipitation gauge in this variant is the highest among all the analyzed variants. A quite similar, spatially, situation characterizes the R_{120} and PFL variant (Figure 5E), in which synchronicity ranged from 44.8 (Międzygórze) to 68.5% (Podzamek). The southern part of the NKR catchment is asynchronous (Międzylesie and Międzygórze precipitation gauges) and is close to 50–55% for precipitation gauges located on tributaries of the NKR (the Biała Lądecka and Bystrzyca Dusznicka rivers).

4. Discussion and Conclusions

The aim of this research was to assess the relationship between potential losses caused by significant floods in Kłodzko town, triggered by rainfall in the upper NKR catchment. It was analyzed using five variants, regarding different periods of rainfall aggregation (from 24 to 120 h) and in terms of the probability of synchronous occurrence. The lowest synchronicity across the entire upper NKR catchment was measured for the R_{24} variant (Figure 5A). Such a result was expected, because floods such as the analyzed ones, in most cases, are not caused by one-day rainfall—in several cases, during the 24 h before the flood peak in Kłodzko town, the rainfall was not recorded in all the studied precipitation gauges. In other cases (i.e., for R_{48}, R_{72}, R_{96} and R_{120}), the synchronicity was spatially differentiated (Figure 5B–E); however, the highest value was always determined for the Podzamek precipitation gauge, and the lowest for the Międzygórze precipitation gauge (with one exception, variant R_{48}—PFL, in which the lowest synchronicity was calculated for the Chocieszów precipitation gauge).

Both calculated PFL and FIZ increase with an increasing water level, but in the case of PFL, the increase is exponential, while the FIZ area shows an inflection point in the graph (Figure 4). This is a consequence of the selected PFL estimation method (it depends on the range and type of flooded area and depth of flooding, while, e.g., flood wave duration is not taken into account) and the topography of the Kłodzko town area, which is located in the mountain river valley; thus, the rising water mainly causes an increase in the depth of the flood in the already-inundated area.

The results obtained are in-line with our previous research [62], especially for variants R_{96} and R_{120}. For the corresponding variants in [62], as well as for rainfall data from the Podzamek precipitation gauge, the synchronicity with the flood peak flow (FPQ) was the highest, although its maximum was around 53.5%, while the synchronicity of rainfall with PFL reached 71.4%. However, in the aforementioned research, another flood data set was analyzed (all floods exceeding the 99th percentile). Additionally, in this study, PFL was based on water level, while in the previous research our analysis was based on discharge (Q). Nevertheless, both studies confirm a significant correlation between floods in Kłodzko town and precipitation measured at the Podzamek gauge.

Regarding the floods selected in this research, it should also be emphasized that at the Kłodzko water gauge in the multi-annual period 1971–2021 (i.e., within 51 years), flood waves exceeding the ’10-year’ water level (i.e., with probability of exceedance $p = 10\%$) were recorded only twice, and the 100-year water level ($p = 1\%$) has never been reached. As mentioned in Section 2.1, the 1997 flood in the Odra River basin is called the “Millennium Flood” or the “Great Flood”, when unit outflow reached 1300 $L \cdot s^{-1} \cdot km^{-2}$ and the historic water level was exceeded by 70 cm [69]. It was an unprecedented in modern history, catastrophic event. Taking it into calculations of the probable maximum flows may lead to overestimation of the theoretical flood water levels. Both overestimation and underestimation of probable flood events is misleading, because in the first case it may result in excessive construction and maintenance costs of flood protection infrastructure, and in the second in the failure of flood protection infrastructure [84]. Such situations will also appear more and more frequently due to climate change, because it may both lead to increases or decreases in European river floods [16], also in Poland, where statistically significant trends in the observed river floods have been identified [19].

The proposed methodology considers only summer floods caused by rainfall, but in the mountains snowmelts can also pose a significant threat to the local communities. Thus, these should also be taken into account to fully understand the flood hazard and risk in such areas. As is mentioned in other studies (e.g., [85–87]), results obtained by applying the copula-based methods are subject to uncertainty, so techniques for these methods' quantification still need to be developed. In terms of the flood losses estimation, a methodology should be developed to also incorporate other flood wave characteristics, such as flood duration, flood water volume and velocity. A comprehensive review of existing flood hazard-assessment methods is presented in [88], and some of them could be incorporated into the PFL estimation.

In conclusion, the introduced methods allow analysis of the spatio-temporal relationships of precipitation and flood risk (in this study, expressed as PFL). The obtained results indicate that (1) the relation between PFL in Kłodzko and 24 h rainfall preceding the flood peak for all precipitation stations is asynchronous, (2) there is a high synchronicity of PFL and cumulative rainfall in the Podzamek station from 48 to 120 h before a flood event, and (3) the probable floods in Kłodzko may be overestimated due to the occurrence of the catastrophic flood of July 1997. These findings can be helpful in preparing and adjusting flood warning systems or planning flood protection measures and infrastructure. As mentioned above, future research should focus on including snowmelt floods into the presented methodology, incorporating quantitative uncertainty estimations, developing PFL calculation methods which not only include depth of flooding, and assessing the impact of climate change on flood risk. Another interesting research topic is an assessment of the possible under- or overestimation of probable floods, e.g., due to the occurrence of catastrophic events in the past or resulting from the predicted climate change.

Author Contributions: Conceptualization, A.P., D.W. and W.W.B.; methodology, A.P., D.W., W.W.B. and L.S.; software, A.P.; validation, A.P.; formal analysis, A.P.; investigation, A.P. and D.W.; resources, A.P. and D.W.; data curation, A.P. and D.W.; writing—original draft preparation, A.P.; writing—review and editing, A.P., D.W., W.W.B. and L.S.; visualization, A.P.; supervision, D.W., W.W.B. and A.P.; project administration, A.P.; funding acquisition, D.W., L.S. and A.P. All authors have read and agreed to the published version of the manuscript.

Funding: The research was carried out under the "GEO-INTER-APLIKACJE" project (No. POWR. 03.02.00–00-I027/17) implemented at the Faculty of Geographical and Geological Sciences of Adam Mickiewicz University in Poznań, Poland. Adam Perz has been granted by scholarship of the Adam Mickiewicz University Foundation and the Kulczyk Foundation for the academic year 2022/2023.

Data Availability Statement: Data available on request due to restrictions e.g., privacy or ethical. The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors acknowledge the help of Patryk Nowicki, Katarzyna Pędziwiatr, Olga Konieczna and Łukasz Trojnarski from Sweco Polska Sp. z o.o. in processing GIS data and potential flood losses estimation. The authors would like to thank the editors and reviewers for their comments and suggestions, which have significantly helped to improve the quality of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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