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VARIABILITY OF THE RUNOFF COEFFICIENT FOR SELECTED CATCHMENTS IN THE UPPER VISTULA RIVER CATCHMENT

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ABSTRACT

The runoff coefficient is one of the basic hydrological characteristics of the catchment. It can be determined using multiannual, periodic, or annual data measurement sequences. The variability of the runoff coefficient can be influenced by the terrain, the land cover, and the land-use in the catchment, among other things.

The present study is an attempt to analyse changes in the runoff coefficient over a period of 30 years (1984–2013) for 49 gauging sections located in the Carpathian part of the Upper Vistula catchment. An additional analysis was carried out to study the impact of changes in the land cover and land-use of the catchment on the value of the runoff coefficient. Rainfall and daily flows data was made available by IMGW-PIB, whereas land cover and land-use data of the catchment come from the CORINE Land Cover system (1990, 2000, 2000, and 2012).

Keywords: runoff coefficient, catchment land use, CORINE Land Cover map

INTRODUCTION

Compared with other European countries, Poland has relatively small water resources (Bartnik 2005, Kundzewicz et al. 2010, GUS 2017). These resources are characterized by uneven spatial distribution. A unique area in this respect is the Upper Vistula catchment, which has greater surface water resources than the rest of the country. This is related, among other things, with the terrain, which affects the intensity of precipitation and higher surface runoff; that in turn has an impact on increasing the outflow from the catchment (Marcinkowski and Winter 2012). The capacity of the Carpathian catchment increases with the increase of the catchment height: from less than 8 $dm^3 \cdot s^{-1} \cdot km^{-2}$ in sub-montane catchments bordering Kotlina Sandomierska, to 15–20 $dm^3 \cdot s^{-1} \cdot km^{-2}$ in the high parts of the Beskid mountains, to over 50 $dm^3 \cdot s^{-1} \cdot km^{-2}$ in the Tatra part of the Dunajec catchment (Soja 2002).

The runoff coefficient is one of the basic hydrological characteristics of any catchment (Vlčková et al. 2009). It denotes part of the rainfall that is transformed into the river's outflow (Pociask-Karteczka 2006), i.e. part of the rainwater that has flowed from the area (Bajkiewicz-Grabowska, Mikulski 1999; Vlčková et al. 2009).

The type of coverage and method of land development significantly affect the outflow from the catchment. Currently, one of the most important impacts of urbanization on the water cycle is increasing the area of impermeable surfaces (Chormański et al. 2012). An increase in the area of anthropogenically-modified land usually takes place at the expense of agricultural and forest areas, which adversely affects the retention capacity of the catchment.

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The influence of the changes in land cover on runoff was studied by Tourbier and Westmacott (1981), who noticed that increasing the sealing of the land by 30–50% causes a threefold increase in surface runoff, and by about 75–100%, even a fivefold increase (Chormański et al. 2012 for Tourbier and Westmacott 1981).

The aim of the present study is to assess the variability of the runoff coefficient from the catchment in the period of 1984–2013, in the Carpathian part of the Upper Vistula catchment. The analysis was based on sequences of daily flows in 49 water gauging stations, and on average daily precipitation determined for these water-gauging stations on the basis of daily rainfall sequences (measured at 48 posts). The correlation between the runoff coefficient and the changes in land cover and land use was also determined. In order to determine the land cover and land use, data from the CORINE Land Cover system was used, obtained and developed within the framework of the European Environment Agency in the years 1990, 2000, 2006, 2012 for the area of the European Union Member States.

STUDY AREA AND DATA

The study used 30–year rainfall sequences, recorded in 48 rainfall stations, and daily flow sequences recorded in 49 water gauging stations located in the Carpathian area of the Upper Vistula catchment, throughout the period of 1983–2013. The data has been made available by IMGW–PIB. The location of water gauging stations is shown in Figure 1.

Three of the 49 water gauging stations are located in the Eastern Beskidy mountains, 2 are located in the Central Carpathians, and the remaining 44 in the Outer Carpathians (according to the classification by Kondracki 2000 and Pociask-Karteczka 1995).

The water gauging stations enclose catchments of the area between 24.7 km^2 and 5647 km^2. Surface area of 29 out of 49 catchments remains in the range of 100–1000 km^2 (see: Fig. 2). Zero points of the water gauging stations range from 190.7 up to 636.4 m above sea level. The majority of the measuring stations (30 out of 49) are located at an altitude above 300 m a.s.l. Slopes of the watercourses are between 0.33 and 10.2% (on average about 2%), whereas 35 catchments have a circularity ratio lower than 0.5.

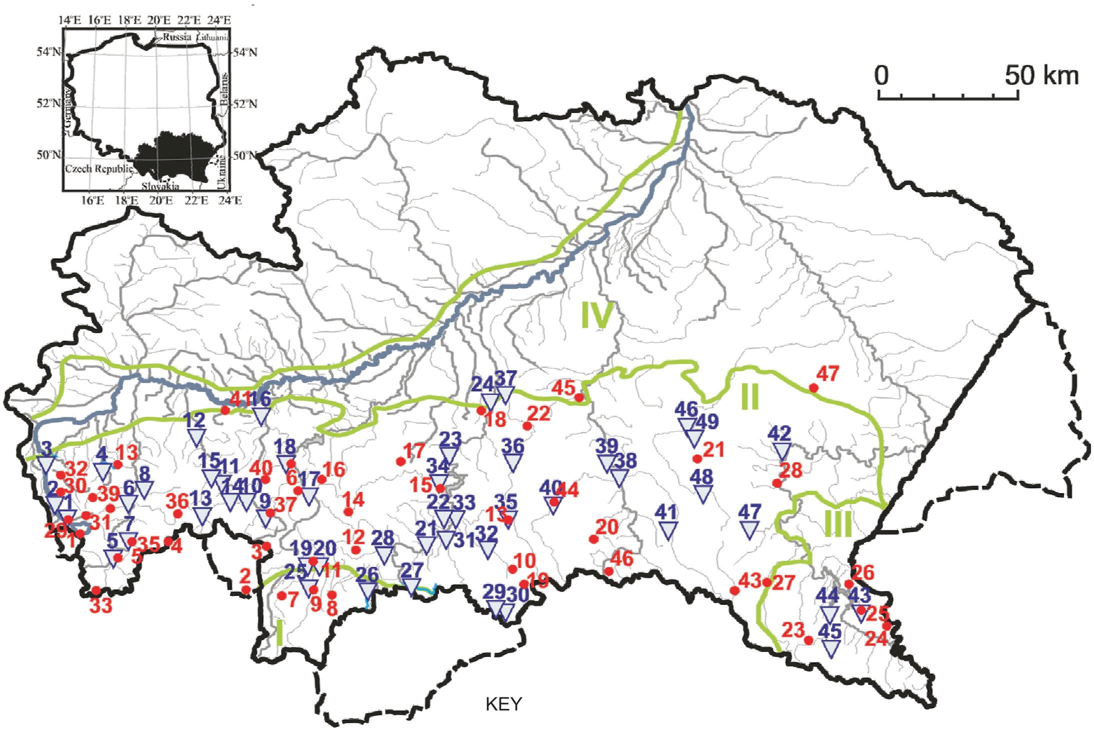
Three thematic layers of the CORINE Land Cover (CLC) system from 1990, 2000, 2006 and 2012 were applied in order to determine land coverage and land development in all of the 49 catchments, including: anthropogenic areas, agricultural areas, forest areas.

In the period of 1990–2012, the median of the land development rate increased from 2.8% up to 5.2%, while the median of agricultural areas decreased from 41.9% down to 36.2% (see: Fig. 3).

According to data from the year 2012, the afforestation of the analysed catchments ranged from 31.3% to over 93%, the share of agricultural areas, from 4.6% to 65.8%, and of anthropogenic areas, from 0% to 30.4% (the Żabniczanki catchment up to the Żabnica water gauge is not developed anthropogenically).

Figure 4 shows the correlation between the average daily flow within the 1984–2013 period, and the size (surface) of the catchment area. The correlation between these variables is high, and the linear correlation coefficient amounts to 0.99.

Fig. 1. Location of selected water gauge stations and precipitation measuring stations in the Upper Vistula River catchment



- rivers
- Polish border of the Upper Vistula catchment
- border of the Upper Vistula catchment
- Upper Vistula
- 14 water gauging stations
- 33 precipitation measuring stations
- Borders between physico-geographical units according to Kondracki (2000) and Pociask-Karteczka (1995):
  I. Central Western Carpathians
  II. Outer Western Carpathians
  III. Eastern Beskidy Mts.
  IV. Eastern Sub-Carpathian region

WATER GAUGING STATIONS

1 Wisła	11 Sucha	21 Gołkowice	31 Stary Sącz	41 Zboiska
2 Ustroń Obłaziec	12 Wadowice	22 Nowy Sącz	32 Łabowa	42 Dynów
3 Skoczów	13 Zawoja	23 Czchów	33 Nowy Sącz	43 Polana
4 Mikuszowice	14 Skawica Dolna	24 Zgłobice	34 Jakubkowice	44 Terka
5 Rajcza	15 Sucha Stryszawka	25 Szaflary	35 Grybów	45 Kalnica
6 Żywiec	16 Radziszów	26 Niedzica	36 Ciężkowice	46 Żarnowa
7 Żabnica	17 Kasinka Mała	27 Szczawnica	37 Koszyce Wielkie	47 Nowosielce
8 Łękawica	18 Stróża	28 Tylmanowa	38 Żółków	48 Iskrzynia
9 Jordanów	19 Nowy Targ	29 Muszyna	39 Krajowice	49 Godowa
10 Osielec	20 NT Kowaniec	30 Muszyna Milik	40 Gorlice	

PRECIPITATION MEASURING STATIONS

1 Istebna-Stecówka	11 Kowaniec	21 Krasna	31 Ustroń Równica	41 Straconka
2 Chyżne	12 Ochotnica Górna	22 Tuchów	32 Górki Wielkie	42 Brzeźnica
3 Harkabuz	13 Grybów	23 Cisna	33 Rycerka Górna	43 Wisłok Wielki
4 Korbielów	14 Półrzeczki	24 Lutowiska	34 Rajcza	44 Gorlice
5 Lubień K/Rabki	15 Świdnik-Tęgoborze	25 Polana	35 Żabnica	45 Pilzno
6 Stróża	16 Węglówka	26 Teleśnica Oszwarowa	36 Koszarawa	46 Wyszowadka
7 Ratuów	17 Rozdziele	27 Szczawne	37 Jordanów	47 Kańczuga
8 Białka-Tatrzańska	18 Wojnicz	28 Temeszów	38 Lipowa	
9 Szaflary	19 Tylicz	29 Wisła-Głębce	39 Szczyrk	
10 Huta	20 Bartne	30 Wisła-Malinka	40 Bogdanówka	

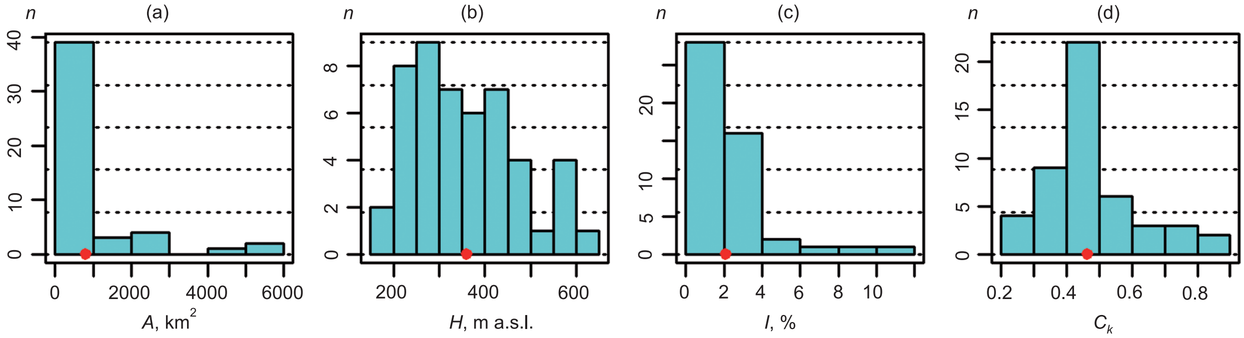


Fig. 2. Distribution of number *n* of catchments versus: (a) area *A* of the catchment enclosed by the water gauging station, (b) water gauging station elevation *H*, (c) river slope *I* and (d) circularity ratio of catchment C_k

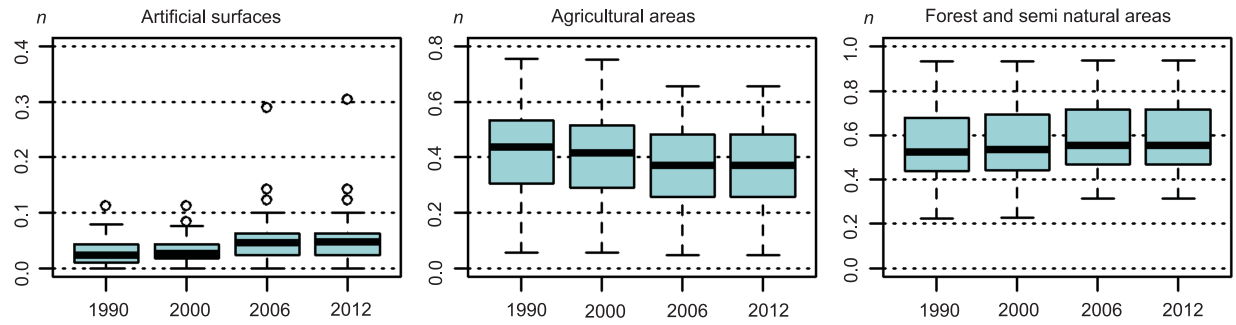


Fig. 3. Ratio *n* of the given type of land-use in the catchment; for the 49 catchments of the Upper Vistula River. The lower and the upper borders of the box are the first and third quartiles; whereas the line inside the box is the median value. The whiskers extend to 1.5 × of the interquartile range. The points outside the whiskers represent statistical outliers

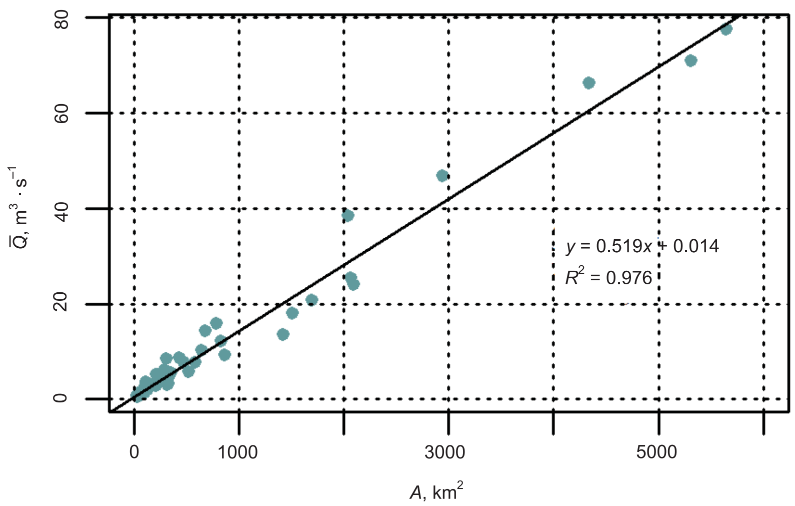


Fig. 4. Scattergram of correlation between the average daily flow and size of the catchment area, in the Upper Vistula River catchment

METHODOLOGY

The average daily precipitation (mean sum of daily rainfall) was calculated by the method of inverse distances based on the sequences of measured daily rainfall (Szczepanek 2003 after Meijerink et al. 1994). This method of estimating the average rainfall was developed in 1972 by the US National Weather Service. For each water gauging station, the average drop $\overline{P}_k$ in each subsequent k-day is calculated on the basis of data sequences from *i*-stations:

$$P_k = \frac{\sum_{i=1}^{n}(W_i P_i)}{\sum_{i=1}^{n} W_i} \tag{1}$$

$$W_i = \frac{1}{L_i^2} \tag{2}$$

where:
- P_k – amount of precipitation in the studied point k [mm],
- P_i – amount if measured daily rainfall in the *i*-th station [mm],
- w_i – weight ascribed to the *i*-th station [–],
- L_i – distance between the *i*-th station and the water gauging station [m].

Based on the average daily precipitation amounts, and daily flow rates, annual runoff coefficients were determined. The runoff coefficient describes the potential capacity of the catchment, and it is expressed by the ratio of the amount of water flowing out of the catchment area at the time, to the amount of water at the same time falling in the form of precipitation to the catchment area (Pociask-Karteczka 2006):

$$C_r = \frac{H}{P} \tag{3}$$

where P is the annual sum of the average daily precipitation amounts, calculated for the given water-gauging station:

$$P = \sum_{k=1}^{n} P_k \tag{4}$$

H is the annual runoff layer from the given water-gauging station [mm]:

$$H = \frac{V}{1000\,A} \tag{5}$$

where: A is the size (surface) of the catchment area [km^2], and V – is the volume of the runoff [m^3]:

$$V = 86\,400 \sum_{k=1}^{n} Q_k \tag{6}$$

where k is the average daily flow intensity in the k-th day [m^3/s], whereas n – is the number of days in the year, in which the flow is calculated.

On the basis of thus determined annual runoff coefficients of C_r, average runoff coefficients were determined: C_w – from the multi-year period, and C_c – for the years obtained from the CORINE Land Cover (C_c) system (1984–1990, 1991–2000, 2001–2006, 2007–2012).

In the present study, in order to determine trends in the variability of C_w, C_r and C_c coefficients, a significance test for the linear coefficient of regression was used (Węglarczyk 2010). This test consists in verifying the hypothesis H_0 (a = 0) for the zero of the directional a coefficient of the straight line regression (that is, the hypothesis of no linear trend) $y = a \cdot x + b$, where $x = C_w$, C_r or C_c.

RESEARCH RESULTS AND DISCUSSION

Average annual rainfall

Based on the data from precipitation stations (selected from 48 available stations), in each of 49 water gauging stations, according to the formula (1), the daily average rainfall P_k and the annual average rainfall P were determined for individual water gauging stations. On average, in the given gauging station, about six stations were considered, although in seven cases more than ten stations were taken into account (see: Fig. 5a). The average distance between the precipitation measuring station and the water gauging station was 24.4 km (see: Fig. 5b), and the maximum distance was around 96 km (see: Fig. 5c).

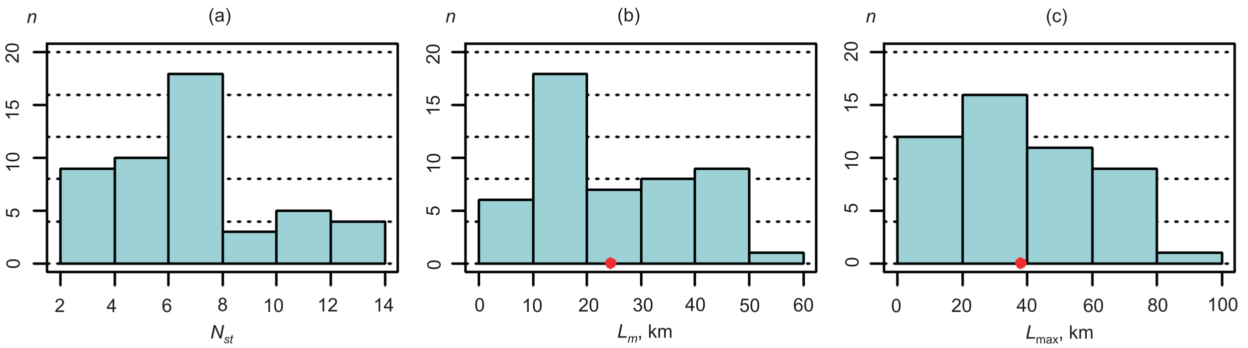


Fig. 5. Number of precipitation measuring stations N_{st}, used to calculate the average precipitation (as well as the average distance L_m and maximum distance L_{max} from the gauging station) in 49 water gauge profiles in the Upper Vistula River catchment. Red dots mark the average values

The correlation between the annual average precipitation P and the zero point of the water gauge is presented in Figure 6. The value of the linear correlation coefficient between P and H is 0.34 and is statistically significant at the 5% significance level – according to the significance test of Pearson's linear correlation coefficient (NIST 2018).

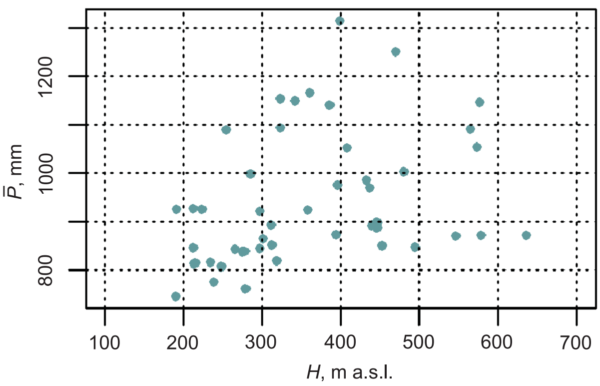


Fig. 6. Scattergram of correlations between the average annual precipitation and the elevation of the zero point of the gauging station in the Upper Vistula River catchment

Spatial distribution of the C_w runoff coefficient in the given multi-year period

The average runoff coefficient C_w in the multi-year period in the studied area varies from 0.35 in Radziszów (see: Fig. 7, No. 16) to 0.9 in Kalnica (see: Fig.7, No. 45). High values of the C_w coefficient are observed in the southern, higher part of the studied area.

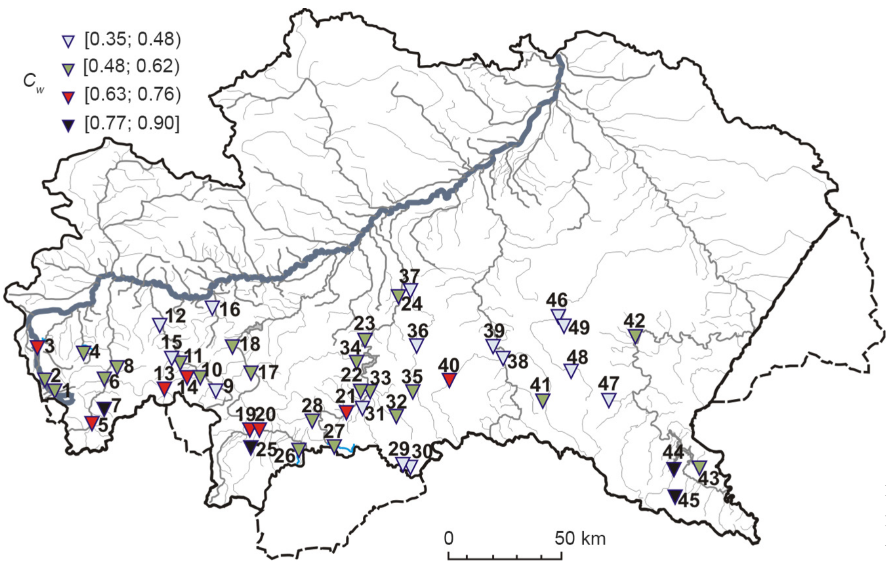


Fig. 7. Spatial distribution of the runoff coefficient C_w from the multi-year period, in the Upper Vistula River catchment

The C_w coefficient is significantly correlated with the zero point of the water gauging station (see: Fig. 8), with the correlation coefficient being 0.69.

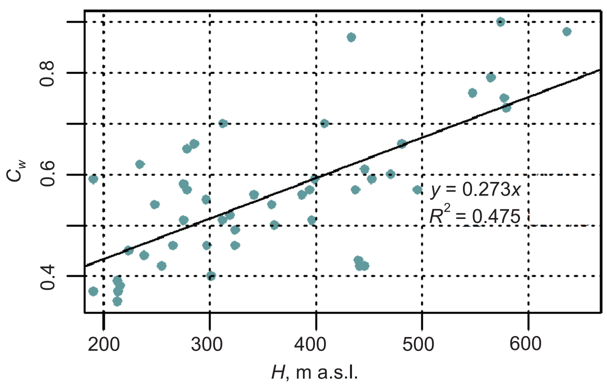


Fig. 8. Correlation between the runoff coefficient C_w from the multi-year period, and the elevation H of zero point of the water gauging station in the Upper Vistula River catchment

Variability of the annual runoff coefficient C_R

The trend of the average annual runoff coefficient C_r in 10 out of 49 water gauging stations is statistically significant at the 5% significance level. In seven catchments (Wisła, Ustroń-Obłaziec, Mikuszowice, Nowy Targ Kowaniec, Zgłobice, Kalnica, and Żarnowa), the annual runoff coefficient in the thirty years under investigation increases, while in three catchments (Żabnica, Zawoja, and Skawica Dolna), it decreases (see: Fig. 9).

Variability of the average runoff coefficient in the periods of: 1984–1990, 1991–2000, 2001–2006, and 2007–2012

The average runoff coefficients C_c in the periods of 1984–1990, 1991–2000, 2001–2006, and 2007–2012 were also calculated. So defined multi-annual periods result from the CORINE Land Cover system, and they facilitate making a comparison between the variability of runoff coefficients and land cover with land development of the catchment.

The average C_c runoff coefficient in the periods of 1984–1990, 1991–2000, 2001–2006, and 2007–2012 increases in the case of 11 water gauging stations, and it decreases in the case of 3 gauging stations, thus presenting a trend at the level of 5% significance (see: Fig. 10).

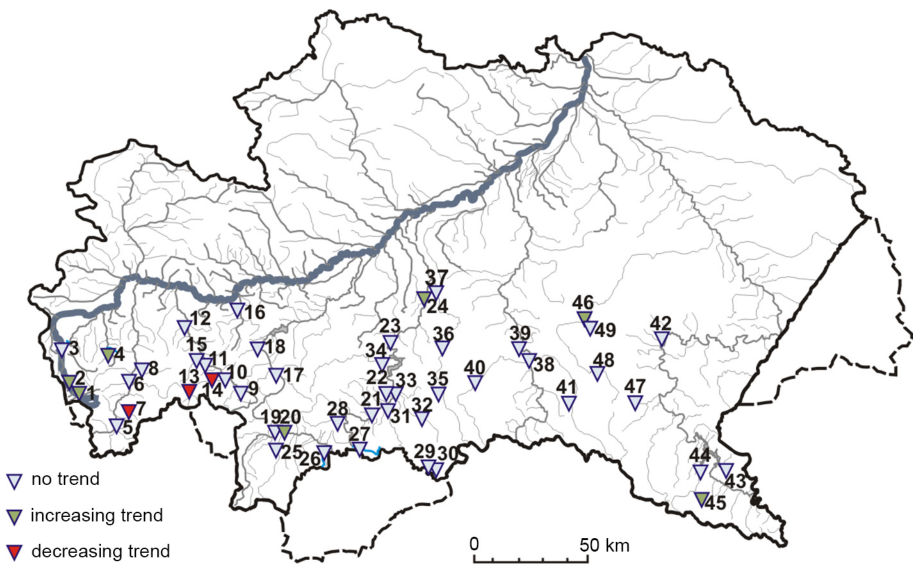


Fig. 9. Location of water gauging stations with information on significant trends of the annual runoff coefficient C_r in the Upper Vistula River catchment

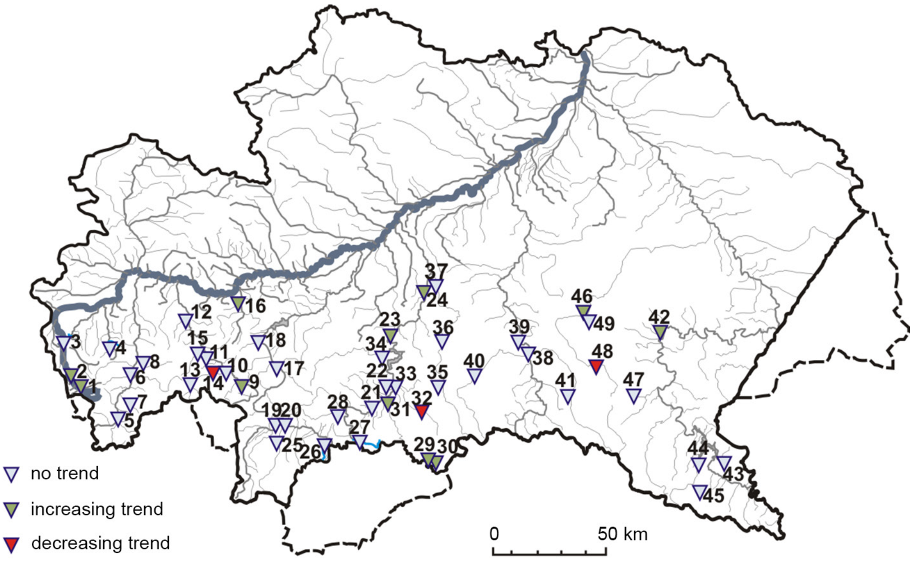


Fig. 10. Location of water gauging stations with the information on significant trends of the runoff coefficient C_c in the Upper Vistula River catchment

Impact of the changes in land cover and land development in the catchment on runoff coefficient in the periods of: 1984–1990, 1991–2000, 2001–2006 and 2007–2012

The analysis of the thematic layers of the CORINE Land Cover system in the analysed periods shows that in the upper Vistula river catchment basin, the size of anthropogenic areas increases, while the sum of forest and agricultural land (mainly arable land) is going down.

The average share of anthropogenic land and afforestation increases throughout the analysed period. In the years 2001–2012, this increase is greater, with a marked decline in the share of agricultural land (see: Fig. 11). The value of the average C_c coefficient slightly increased in 1984–2006, after which it slightly decreased (see: Table 1). Changes to this coefficient are virtually negligible.

Table 1. Average changes in land-use, and runoff coefficient C_c in the Upper Vistula River catchment

	1984–1990	1991–2000	2001–2006	2007–2012
Average runoff coefficient	0.547	0.559	0.561	0.557
Average share of anthropogenic areas	2.81%	3.27%	5.13%	5.19%
Average share of agricultural areas	41.87%	40.57%	36.28%	36.21%
Average share of forests and semi-natural ecosystems	54.86%	55.64%	58.07%	58.08%
Average share of green areas	96.73%	96.21%	94.35%	94.28%

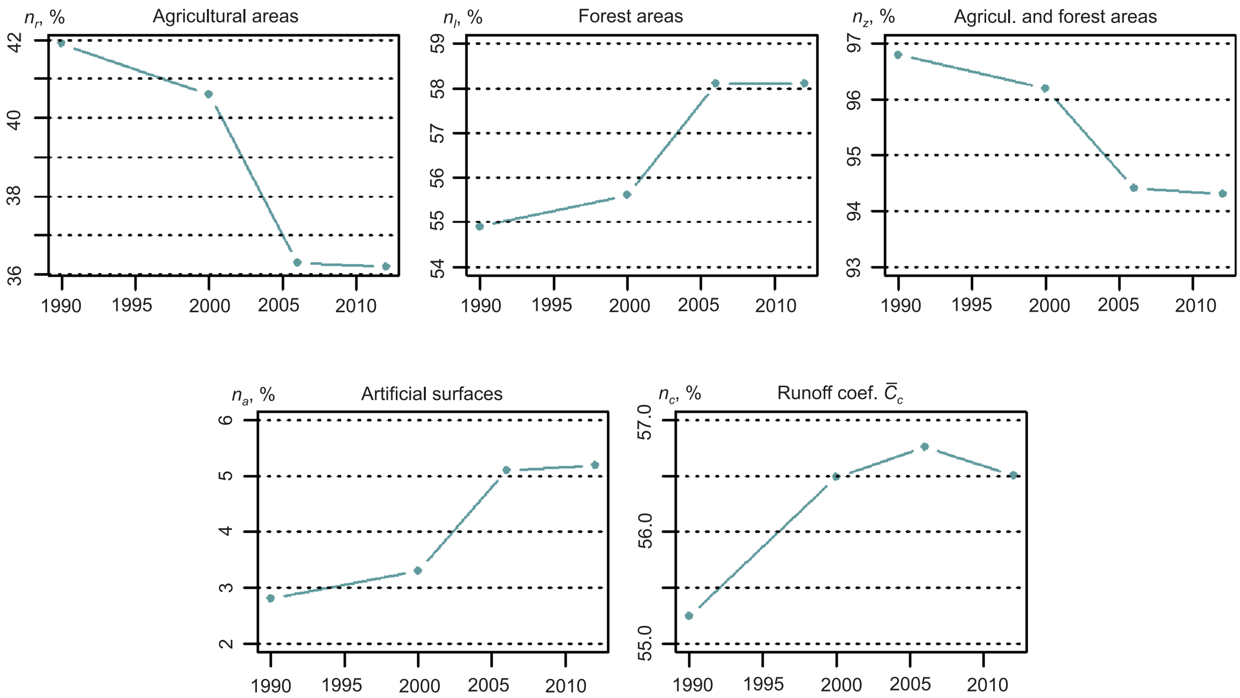


Fig. 11. Changes in land-use and runoff coefficient C_c in the Upper Vistula River catchment

CONCLUSIONS

Based on the conducted analysis, it can be concluded that:

1. The tested catchments are characterized by diversified terrain and landforms, as a result of which significant fluctuations in the average precipitation amounts (744–1314 mm) have been observed. This affects the significant variability of the C_w coefficient (0.35–0.9) from the multi-year period.
2. The runoff coefficient is indicative of what part of the water coming from precipitation flows away from the catchment. In the studied multi-year period, the higher its value, the lower the losses from evaporation. Therefore, in the mountains, where the observed temperatures (and the evaporation) are lower than in the submontane and lowland areas, and where water flows quickly down the slopes, the runoff coefficient is the highest (Dynowska and Tlałka 1982). The C_w coefficient is significantly correlated with the altitude of zero point of the water gauging station. This results from the location of the water gauge, form of the terrain and land cover as well as the morphology of the catchment.
3. For 20% of the surveyed water gauging stations, the trend of the average annual C_r runoff coefficient is statistically significant at the 5% significance level (in seven catchments the trend is increasing, whereas in three catchments it is decreasing).
4. In the years 1990–2012, the average size of anthropogenic areas increased by about 2.5%, whereas green areas decreased by about 2.5%. These changes are mainly related to the reduction of agricultural areas by approximately 5%. One of the many reasons for the increase in the C_c runoff coefficient may be the reduction in the size of green areas, and the increase in the size of anthropogenic areas.

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ZMIENNOŚĆ WSPÓŁCZYNNIKA ODPŁYWU Z WYBRANYCH ZLEWNI NA OBSZARZE ZLEWNI GÓRNEJ WISŁY

ABSTRAKT

Współczynnik odpływu jest jedną z podstawowych charakterystyk hydrologicznych zlewni. Można go określić uwzględniając wieloletnie, okresowe lub roczne ciągi pomiarowe. Na zmienność współczynnika odpływu mogą mieć wpływ m.in. ukształtowanie terenu, pokrycie i zagospodarowanie zlewni.

Niniejsze opracowanie stanowi próbę analizy zmian współczynnika odpływu na przestrzeni 30 lat (1984––2013) dla 49 przekrojów wodowskazowych zlokalizowanych w karpackiej części zlewni Górnej Wisły. Dodatkowej analizie poddano wpływ zmian w pokryciu i zagospodarowaniu zlewni na wartości współczynnika odpływu. Dane dotyczące opadów i przepływów dobowych zostały udostępnione przez IMGW-PIB, natomiast dane dotyczące pokrycia i zagospodarowania zlewni pochodzą z systemu CORINE Land Cover (1990, 2000, 2006, 2012).

Słowa kluczowe: współczynnik odpływu, pokrycie zlewni, mapa pokrycia terenu CORINE