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# LONG-TERM VARIABILITY OF RUNOFF OF THE UPPER NOTEĆ RIVER (CENTRAL POLAND) IN 1981-2016

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**Abstract.** The aim of this paper is to determine the long-term variability of runoff of the upper Noteć River in the period 1981-2016. The study area includes the upper Noteć River catchment located in the central part of Poland. Water resources of the upper Noteć River are among the lowest in Poland. Annual precipitation recorded at 5 meteorological stations was used for analysis. Annual precipitation totals in 1981-2016 ranged from 491.5 mm (station Kołuda Wielka) to 534.9 mm (Strzelno). Average specific runoff of the Noteć River ranged from 2.05 to 3.33 $dm^{3}\cdot s^{-1}\cdot km^{-2}$. Increasing trends in annual precipitation totals were recorded over the period under study, but this did not translate into increasing trends in flows. A slight upward trend in flows was recorded only at the Noć Kalina station and included mean and minimum annual flows. The analysis of flow variability index Cv, coefficient k and number of days with low flows below flow Q70% and Q95% showed that the flow of the upper Noteć River at the Łysek, Noć Kalina and Pakość stations is disturbed.
**Keywords:** variability indices, precipitation, flow, upper Noteć River, Poland

## 1 INTRODUCTION

Climate change and increasing demand for water resulting from human activities are putting water resources under increasing pressure. This is especially true for regions with scarce water resources, which are struggling to provide adequate water for society and the economy. As a result, water-related conflicts can occur in many parts of the globe (Kowalczak and Kundzewicz, 2011).

Water resources are highly variable in time and varied in space due to the variable spatial and temporal distribution of precipitation, the pattern of which is random. Precipitation is the driving force behind flow activation in rivers (Shanafield et al. 2020). Changes in precipitation distribution can result in extreme events, which include floods and droughts. The occurrence of heavy and more frequent precipitation can lead to more frequent flooding. In turn, lack of precipitation can lead to the occurrence of droughts and subsequent desertification of areas. Water resources are therefore extremely sensitive to climate change (Kubiak-Wójcicka 2020). The assessment of water resources and their variability is a key element that can determine the economic development of a region or country. In recent years, a number of studies have been conducted on the impact of climate change on water resources in Europe (Pekarova et al. 2006; Stahl et al. 2010; Dobrovol'skii 2018; Dunea et al., 2021; Kubiak-Wójcicka et al. 2021b). Studies of runoff variability, as one of the most important components of the water cycle affected by climate change, have been made for many regions of Europe (Bormann 2010; 2012; Stonevičius et al. 2014; Jaagus et al. 2017; Barbalić and Kuspilić 2014; Marinică et al. 2018; Kubiak-Wójcicka and Machula 2020). Runoff variability in Poland has been studied by many authors (Jokiel and Stanisławczyk 2012; Wrzesiński and Sobkowiak 2018; Tomaszewski 2018; Bartnik and Moniewski 2019; Mostowik et al. 2019; Jokiel and Tomalski 2021). Areas with the least water resources were the focus of Ilnicki et al. (2014) and Jamorska (2013).

The aim of the study is to investigate the variability and dynamics of flows by determining trends and indices of variability of flows of the upper Noteć River in a multi-year perspective. The analysis was based on the mean annual values of the Noteć River flows at hydrological stations Łysek, Noć Kalina and Pakość in 1981-2016. The assessment of the formation of the hydrological regime of the upper Noteć River was carried out taking into account the variability of precipitation at meteorological stations located within its catchment. This study aims to highlight the state of water resources in the driest region of Poland and possibilities of their sustainable management during drought and flood periods.

## 2 STUDY AREA AND METHODS

The study covered the upper Noteć River catchment located in the central part of Poland. The upper Noteć catchment is located within historical region of Kujawy. This region is counted among the most important regions of Poland because of agricultural production. The area contains some of the most fertile soils in Poland - black earth. Arable land within the catchment area accounts for 76.07% of the catchment area, while forest areas account for 11.4%. From the point of view of water resources, the upper Noteć catchment is ranked as one of the regions with the lowest annual precipitation in Poland and the lowest water resources (Kubiak-Wójcicka and Machula 2020; Tomaszewski and Kubiak-Wójcicka 2021). The upper Noteć River is a channelized river, flowing through five lakes, the largest of which is Gopło Lake.

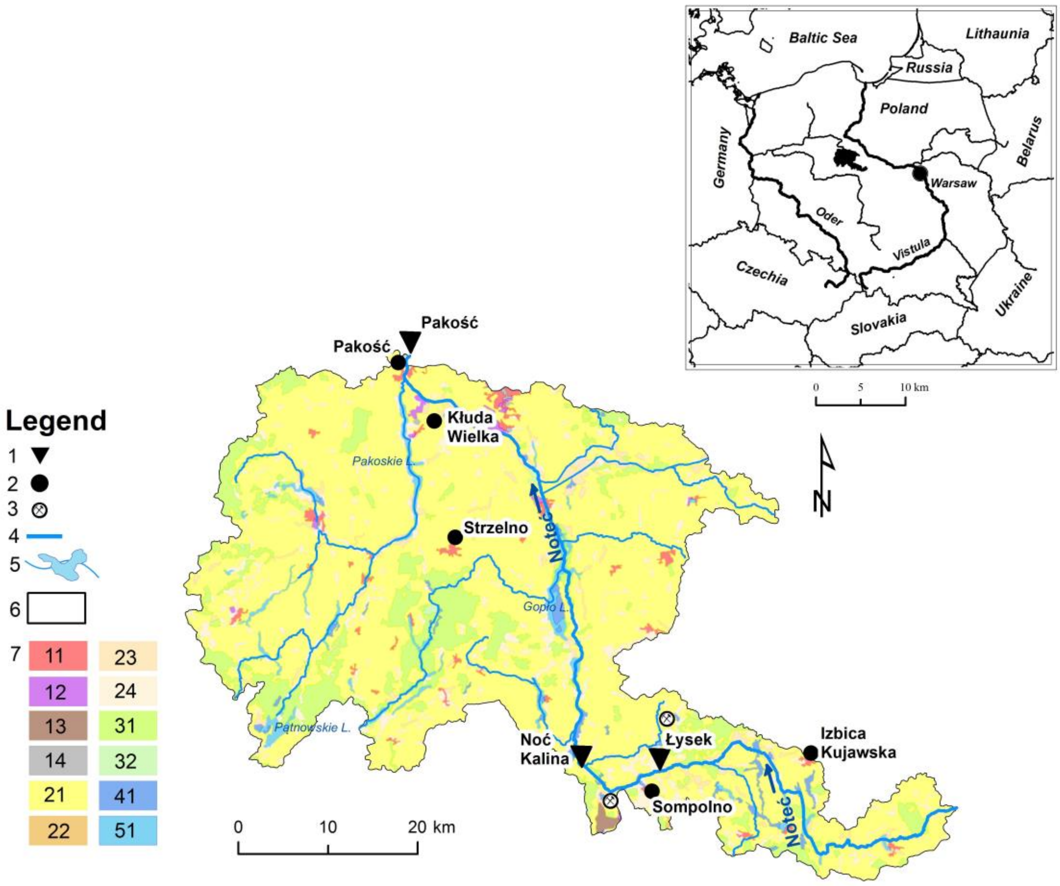


**Figure 1.** Study area of the upper Noteć River. Explanations: 1- hydrological station, 2- meteorological station, 3- lignite open pit, 4- rivers, 5-lakes, 6-watreshed, 7- land use: 11(urban fabric), 12(industrial, commercial and transport units), 13(mines, dumps and construction sites), 14(artificial non-agricultural vegetated areas), 21(arable land), 22(permanent crops), 23(pastures), 24(heterogeneous agricultural areas), 31(forests), 32(scrubs and herbaceous vegetation), 41(inland wetlands), 51(inland waters)

The analysis was based on daily values of Notec river flows recorded at 3 hydrological stations, i.e. Łysek, Noć Kalina and Pakość. Daily values of precipitation for 5 meteorological stations were used to characterize meteorological conditions: Izbica Kujawska, Pakość, Kołuda Wielka, Strzelno and Sompolno. Location of the stations is shown in Figure 1. Hydrological and meteorological data were made available by the Institute of Meteorology and Water Management - National Research Institute and cover the years 1981-2016. Statistical calculations were carried out to characterize the values of flows and precipitation. Based on the daily precipitation values, the annual total precipitation, the number of days without precipitation in each year, and the maximum daily precipitation totals were determined.

The evaluation of flow variability was performed on a multi-year basis based on commonly used hydrological indices (Dery et al. 2016; Kliment and Matoušková 2008).

The highest and lowest flows during the analyzed multi-year period were identified on the basis of daily flow values. In addition, dry and wet years were determined as those in which the values of mean annual flows strongly deviated from the mean values for the multi-year period. The coefficient k, which is the mean value of the flow from the analyzed year (Qi) in relation to the mean value of the flow from the multi-year period (Qsr), was used in the calculation.

$$k = \frac{Qi}{Qsr}$$

The coefficient of variation (Cv) and the multi-year trend of annual flows were used to determine the variability of flows over the year. Coefficient of variation Cv is the quotient of the standard deviation and the arithmetic mean of the annual flows. Coefficient of variation (Cv) of the Noteć River flows was calculated based on the formula:

$$Cv = \frac{\sqrt{\frac{\sum_{i=1}^{n}(Qi - Qsr)^2}{n}}}{Qsr}$$

where:
Qi - flow rate
Qsr - average flow rate
n - cardinality of the sequence

Low-flow periods were identified with reference to threshold level method matching 70 and 95 percentile at a flow duration curve as constant, multiannual truncation level (Q70%, Q95%). A flow with a probability of occurrence of 70% is the threshold value for shallow lows and is most commonly used in hydrological studies (Marx et al., 2018; Kubiak-Wójcicka et al., 2021a). To identify deep lows, a flow with a probability of occurrence of Q95% was adopted, which indicates depletion of renewable water resources in the active water exchange zone and corresponds well with biological indices (Tomaszewski and Kubiak-Wójcicka, 2021). Based on the limits of shallow and deep lows, the number of days per year with flows below Q70% and Q95% was calculated.

## 3 RESULTS AND DISCUSSION

### 3.1 Annual precipitation totals from 1981 to 2016

The analysis of mean annual precipitation sums was carried out at 5 meteorological stations. These are Izbica Kujawska, Pakość, Kołuda Wielka, Strzelno and Sompolno (Table 1). The lowest precipitation within the catchment was recorded at the station Kołuda Wielka (491.5 mm), while the highest at the station Strzelno (534.9 mm). The average annual precipitation recorded at the five stations is 513.8 mm. This value is comparable with data from the period 1999-2018, which for the regions of Wielkopolska and Kujawy was in the range of 500-550 mm. In the years 1971-2015 in Kujawy, precipitation was also in the range of 500-550 mm (Kubiak-Wójcicka 2020). The mean annual precipitation in Poland in the multiyear period 1951-2015 was 625 mm (Kubiak-Wójcicka, 2021). The highest precipitation in the period 1981-2016 occurred in 2010 at all meteorological stations. In that year, the precipitation was higher by up to 66% (Sompolno) compared to the average year of the multiyear period. The lowest precipitation was recorded in 1989 with the exception of the Izbica station, where the lowest precipitation was recorded in 2011. Similarly low annual precipitation totals were recorded in 1982, 2003 and 2015. In these years meteorological droughts were recorded throughout Poland (Bąk and Kubiak-Wójcicka, 2018; Kubiak-Wójcicka 2021). During the analyzed period 1981-2016, a slight increasing trend of precipitation was recorded at all analyzed meteorological stations.

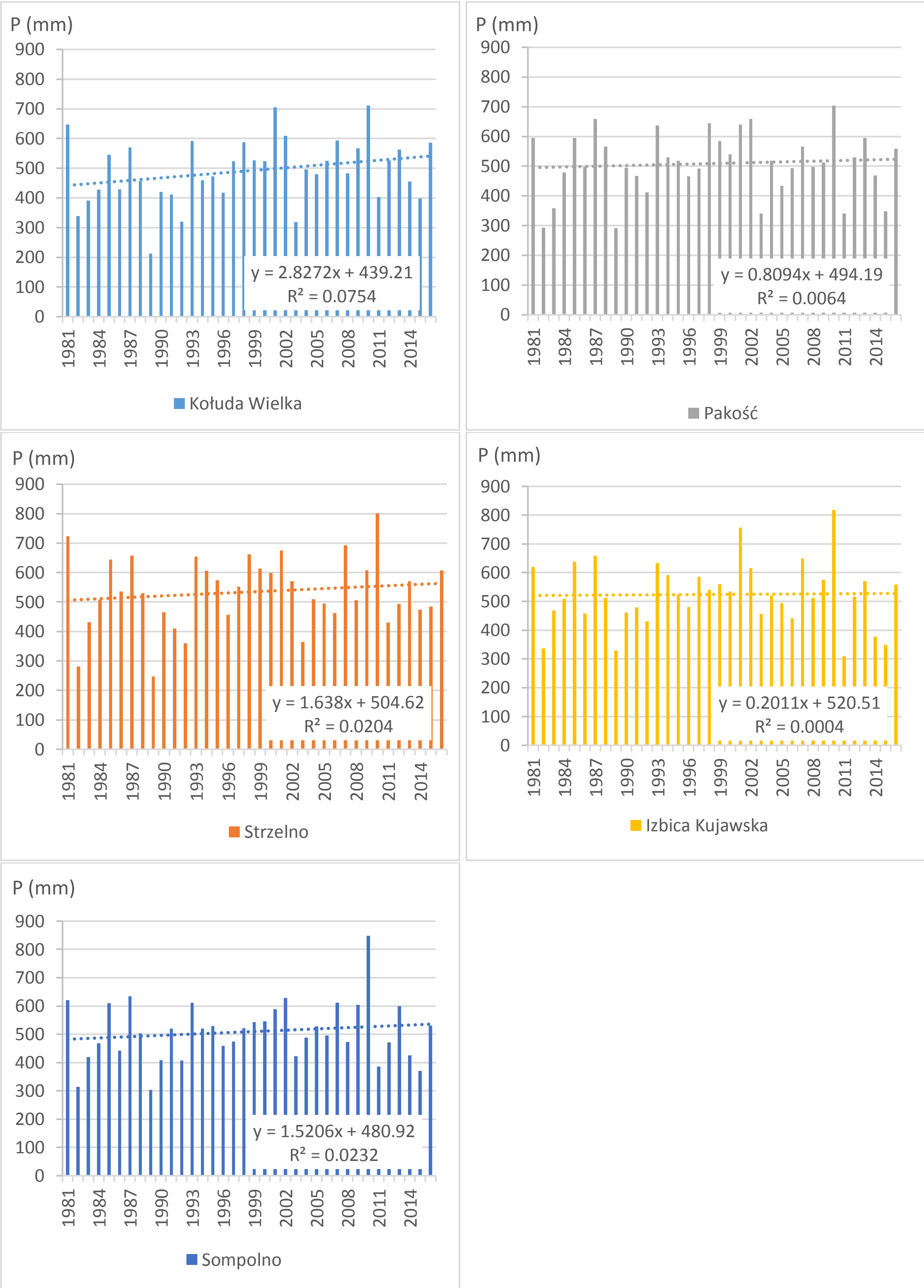


**Figure 2.** Annual sums of precipitation at meteorological stations in the upper Notec river catchment in 1981-2016

**Table 1.** Regression of trends equation for the number of days with precipitation and highest daily sums of precipitation in 1981-2016

| Stations | Average annual precipitation in year 1981-2016 | Number of days in a year with daily precipitation >= 0.1 mm | | Highest daily sums of precipitation (mm) | |
|---|---|---|---|---|---|
| | | Average value | Regression equation | Maximum value | Regression equation |
| Kołuda Wielka | 491.5 | 149.6 | Y=0.665x+137.34 **$R^2$=0.1521** | 81.3 | Y=0.2289X+28.685 $R^2$=0.0378 |
| Pakość | 509.2 | 160.9 | Y=0.3524x+154.43 $R^2$=0.0434 | 67.1 | Y=0.0319x+32.132 $R^2$=0.0006 |
| Strzelno | 534.9 | 142.0 | Y=-0.482x+150.72 $R^2$=0.074 | 69.3 | Y=-0.0334x+34.753 $R^2$=0.0008 |
| Izbica Kujawska | 524.2 | 142.8 | Y=-0.3347x+149 $R^2$=0.0297 | 71.3 | Y=-0.0171x+33.813 $R^2$=0.0002 |
| Sompolno | 509.0 | 155.2 | Y=0.4757x+146.42 $R^2$=0.0962 | 52.1 | Y=0.0605x+30.072 $R^2$=0.0042 |

Analysis of the data showed that at all meteorological stations there was an increasing trend of annual precipitation (Fig. 2). Only at the station Kołuda Wielka the trend line showed statistically significant ($R^2$=0.0754) increasing tendency of annual precipitation amounting to about 28.3 mm/10 years and increasing tendency of the number of days with precipitation >0.1 mm amounting to about 6.7 days/10 years (Table 1). At the remaining meteorological stations, trend lines did not indicate statistically significant increasing or decreasing trends in annual precipitation totals and the number of days with precipitation above 0.1 mm. The analysis of maximum daily precipitation at all stations did not show statistically significant increasing or decreasing trends.

**3.2 Variability of flows on the upper Noteć River in 1981-2016**

During the analyzed period, the highest flows of the Noteć River at the hydrological station Łysek were recorded in 1982, while at the stations Noć Kalina and Pakość in 2011 (Table 2). The lowest flows were recorded in dry years e.g. in 1989 (Noć Kalina) and in 2003 in Pakość. The lack of flow at the Łysek hydrological station in 2015 and 2016 may have been a result of the prolonged and intense drought that occurred in much of Europe (Van Lanen et al. 2016; Hanel et al., 2018; Ionita et al., 2021), including Poland. In Poland, flow disappearance in small watercourses was reported in 2015 (Solarczyk and Kubiak-Wójcicka, 2019). Flow disappearance could also be caused by anthropogenic activities related to opencast lignite mining. During the analyzed 36 years, there is a decreasing trend of maximum annual flows and an increasing trend of minimum annual flows at all analyzed hydrological stations. Fig. 3 presents the course of mean annual flows of the Vistula River in 1981-2016. Despite the increasing trend of annual precipitation totals, the mean specific runoff of the Noteć River in the analyzed multiyear period ranged from 2.5 to 3.33 $dm^3 \cdot s^{-1} \cdot km^{-2}$, which is the lowest value of specific runoff in Poland. The average specific runoff for the multiyear period 1951-2015 in the Vistula basin was 5.4 $dm^3 \cdot s^{-1} \cdot km^{-2}$ and in the Oder basin it was 4.7 $dm^3 \cdot s^{-1} \cdot km^{-2}$ (Kubiak-Wójcicka, 2021).

**Table 2**. Hydrological characteristics of the Noteć River from 1981 to 2016 annual flows

| Hydrological station | Catchment area ($km^2$) | SSQ ($m^3 \cdot s^{-1}$) | WWQ ($m^3 \cdot s^{-1}$) | NNQ ($m^3 \cdot s^{-1}$) | SSq ($dm^3 \cdot s^{-1} \cdot km^{-2}$) |
|---|---|---|---|---|---|
| Łysek | 303.32 | 0.70 | 7.6 | 0.00 | 2.31 |
| Noć Kalina | 426.11 | 1.42 | 15.2 | 0.05 | 3.33 |
| Pakość | 2301.98 | 4.72 | 27.4 | 0.53 | 2.05 |

Note: WWQ – the highest flow in the period, NNQ – the lowest flow, SSQ – average flow, SSq – average specific runoff in the period,

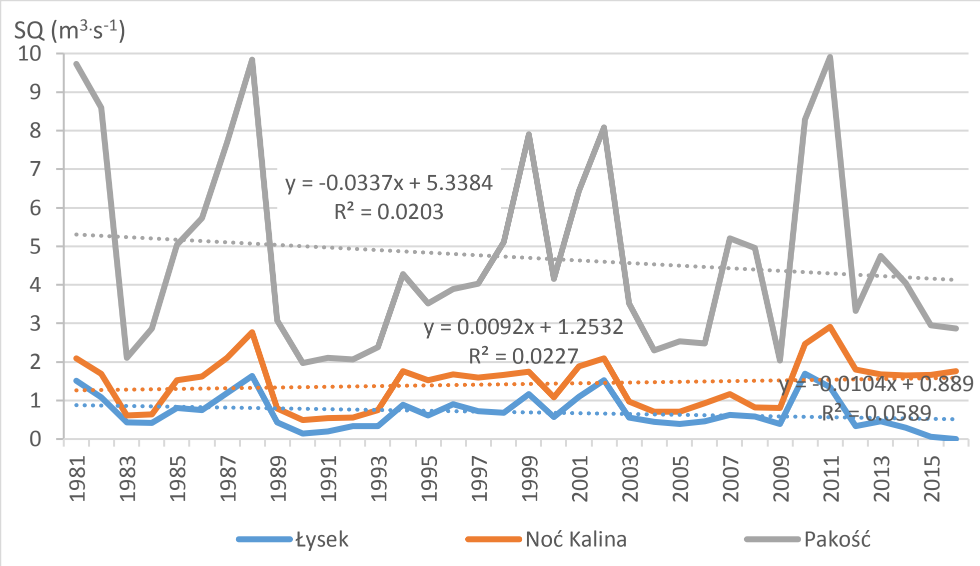


**Figure 3.** Average annual flows on the Upper Noteć River in the years 1981-2016

Comparison of variability of annual flows on the upper Noteć River at all hydrological stations was possible with the use of k index. On its basis (k index) dry, wet and normal years in the analyzed multi-year period were determined (Table 3). The wettest years were 1981, 1987, 1988, 2001, 2002, 2010 and 2011 (k >1.31), whereas the driest years were 1983, 1984, 1989-1993, 2004-2006 and 2006 (k<0.70), which were recorded at all stations.

**Table 3.** Values of the k coefficient on hydrological stations in years 1951-2015

| Station/Year | Łysek | Noć Kalina | Pakość |
|---|---|---|---|
| **1981** | 2.16 | 1.48 | 2.06 |
| **1982** | 1.54 | 1.20 | 1.82 |
| **1983** | 0.62 | 0.43 | 0.45 |
| **1984** | 0.60 | 0.45 | 0.61 |
| **1985** | 1.15 | 1.08 | 1.07 |
| **1986** | 1.07 | 1.15 | 1.22 |
| **1987** | 1.71 | 1.48 | 1.63 |
| **1988** | 2.33 | 1.95 | 2.08 |
| **1989** | 0.61 | 0.56 | 0.65 |
| **1990** | 0.20 | 0.35 | 0.42 |
| **1991** | 0.28 | 0.38 | 0.45 |
| **1992** | 0.49 | 0.39 | 0.44 |
| **1993** | 0.47 | 0.53 | 0.51 |
| **1994** | 1.27 | 1.24 | 0.91 |
| **1995** | 0.87 | 1.08 | 0.74 |
| **1996** | 1.28 | 1.18 | 0.82 |
| **1997** | 1.03 | 1.12 | 0.85 |
| **1998** | 0.98 | 1.17 | 1.08 |
| **1999** | 1.67 | 1.23 | 1.67 |
| **2000** | 0.81 | 0.77 | 0.88 |
| **2001** | 1.57 | 1.32 | 1.36 |
| **2002** | 2.18 | 1.47 | 1.71 |
| **2003** | 0.79 | 0.69 | 0.75 |
| **2004** | 0.64 | 0.50 | 0.49 |
| **2005** | 0.56 | 0.49 | 0.54 |

| | | | |
|---|---|---|---|
| **2006** | 0.67 | 0.65 | 0.52 |
| **2007** | 0.89 | 0.82 | 1.10 |
| **2008** | 0.83 | 0.58 | 1.05 |
| **2009** | 0.55 | 0.57 | 0.43 |
| **2010** | 2.42 | 1.74 | 1.76 |
| **2011** | 1.92 | 2.05 | 2.10 |
| **2012** | 0.47 | 1.27 | 0.70 |
| **2013** | 0.66 | 1.18 | 1.00 |
| **2014** | 0.42 | 1.17 | 0.86 |
| **2015** | 0.08 | 1.17 | 0.63 |
| **2016** | 0.00 | 1.24 | 0.61 |

| | | | |
|---|---|---|---|
| k | >1.31 | | very wet |
| k | 1.11-1.30 | | wet |
| k | 0.91-1.10 | | normal |
| k | 0.71-0.90 | | dry |
| k | <0.70 | | very dry |

Table 3 presents that there is a predominance of dry and very dry years over wet and very wet years for the entire 1981-2016 multi-year period. The exception is the Noć Kalina station, where the number of wet and very wet years is higher than at the Łysek and Pakość stations. The reason for this condition is the discharge of water from an open pit lignite mine into the Pichna River. The Pichna River flows into the Noteć River above the hydrological station Noć Kalina. The amount of water discharged into the upper Noteć River varied from year to year and depended on the location of the mining works. According to Wachowiak (2011), in 1995-2009 the upper Noteć River was fed with a part of mine waters coming from dewatering of the Lubstów opencast, whereas since 2009 there has been a flow of mine waters from the Tomisławice opencast.

### 3.3 Annual indicators of flow variability

Based on the Cv indices, the annual variability indices of the Noteć River flows were analyzed for the whole 1981-2016 period (Figure 4).

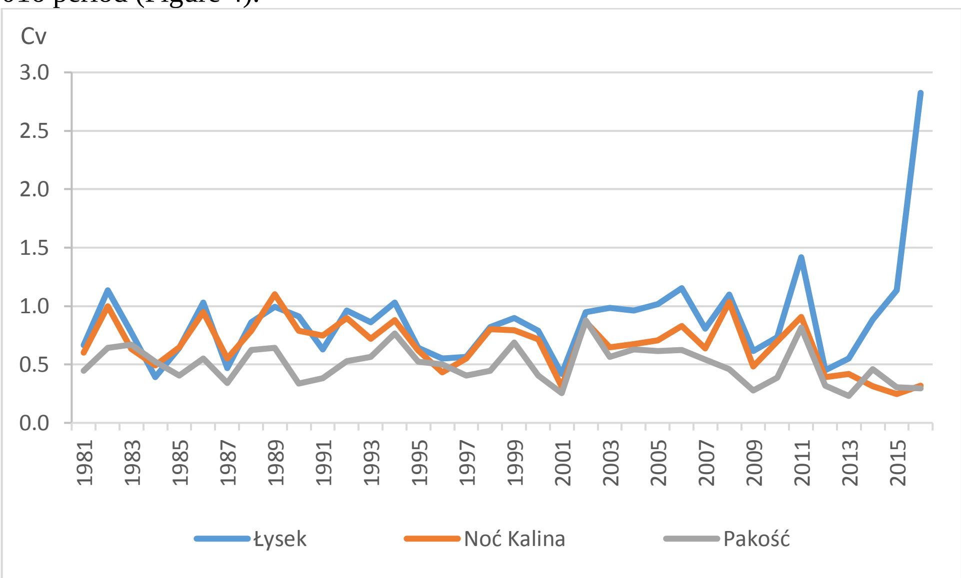


**Figure 4.** Annual coefficient of variation of flows Cv in hydrological stations on the upper Noteć River in the years 1981-2016.

During the analyzed multi-year period 1981-2016, the highest variability of flows occurred at the Łysek station, in which the index Cv ranged from 0.39 to 2.82. Since 2002, there has emerged a clear increase of index Cv. In 2016, this indicator reached its highest value (Cv=2.82) in the analyzed multi-year period. At the station Noć Kalina, the Cv index was significantly lower and ranged from 1.1 to 0.25. The most stable course of flow variability was recorded at the station Pakość. The reason for this state is the stabilization of the Noteć flows as a result of retention activity of the lakes and flow regulation by means of water from Lake Gopło. Cv variability index at Pakość station ranged from 0.23 to 0.88.

Changes in hydrological regime of upper Noteć River are also visible in the number of days with flows lower than flow with probability of occurrence Q70% and Q95% (Figure 5). The highest number of days with lows was recorded at the Łysek station. The average number of days per year with flows below Q70% was 254 days, while with flows below Q95% - 199 days per year. In 2015 and 2016, the flow below the Q70% probability of the flow occurred on all days of the year. It should be noted that from 2010 to 2016, no day with flows below Q70% and Q95% was recorded at the Noć Kalina station.

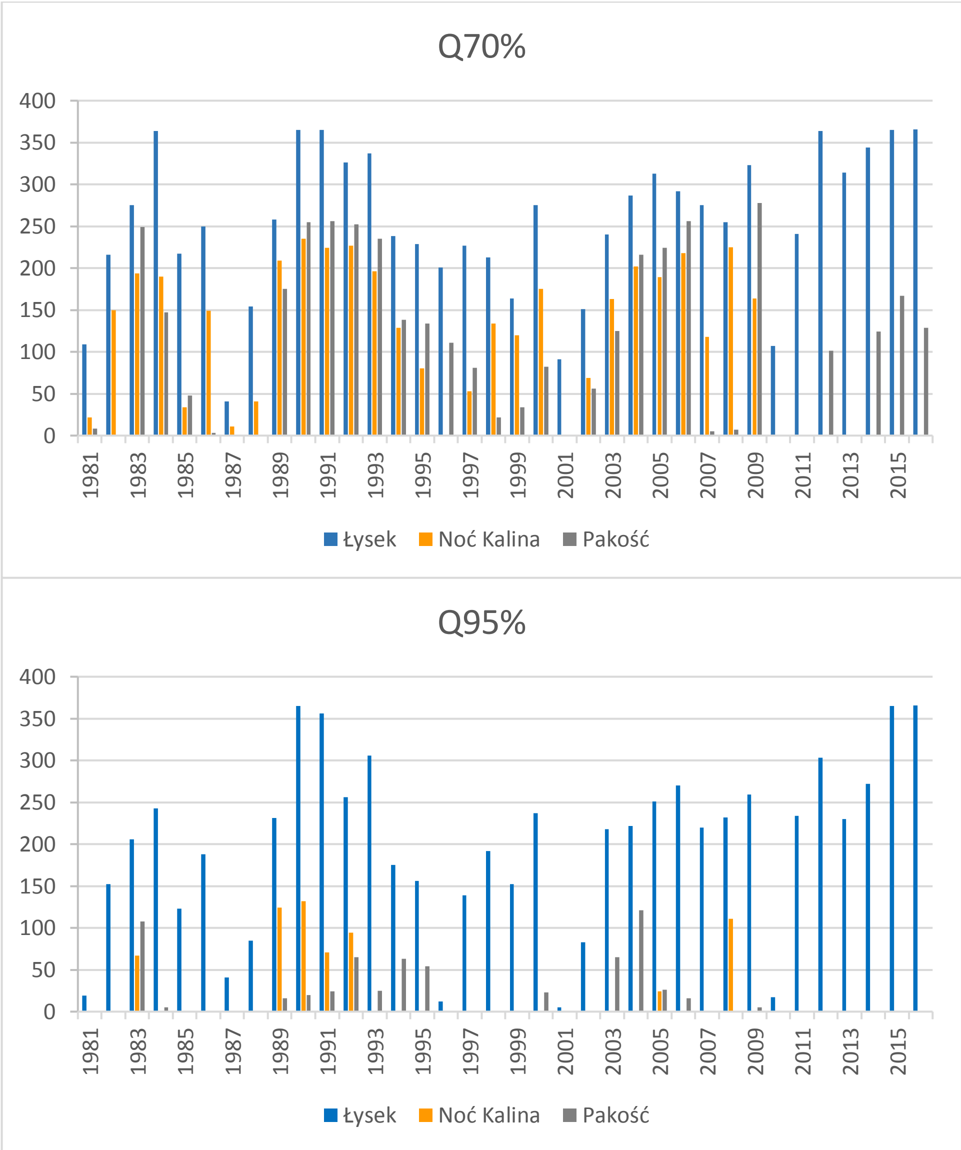


**Figure 5.** Number of days in year with flows below Q70% and Q95%

## 4 CONCLUSIONS

Based on the analysis of precipitation and flows in the upper Noteć catchment it was found that:

- Mean annual precipitation totals show a slight increasing trend in 1981-2016. Statistically significant increasing trends in annual precipitation totals were only recorded at the meteorological station in Kołuda Wielka.

- Annual flows of the upper Noteć River are characterized by high variability during the analyzed period. The greatest downward tendency was observed in maximum flows at the Łysek, Noć Kalina and Pakość stations. Mean annual and low flows of the Noteć River at the analyzed stations showed no clear trend.
- On the basis of the k coefficient it has been established that there is a predominance of dry and very dry years over wet and very wet years in the analyzed multi-year period 1981-2016. An exception is the station Noć Kalina, where the number of wet and very wet years was higher than at the station Łysek and Pakość. This is an effect of water flow from an opencast lignite mine into the Pichny River, which flows into the Noteć River above the Noć Kalina station. An additional factor affecting the flow of the Noteć River in the Pakość profile is water regulation through damming devices and the retention role of lakes.
- Mean annual flow of the Noteć River at the analyzed hydrological stations is disturbed. The highest variability of flows during a year was observed at Łysek station, where the Cv index ranged from 0.39 to 2.82. At this station, also increased number of days with shallow and deep lows was recored, especially in 2010-2016. At other hydrological stations Noć Kalina and Pakość Cv variability coefficient was lower than at Łysek station.

The upper Noteć catchment is located in the historical region of Kujawy, which is extremely important for agriculture. Knowledge of flow regime and assessment of impact of changes on flow rate is crucial for strategic water resources management within the whole basin, especially during prolonged drought. Water abstraction for irrigation of agricultural areas and industrial activities may lead to further decrease in water resources of the upper Noteć River. This situation can be improved by increasing water retention in lakes and reservoirs and by permanent regulation of river runoff using damming devices.

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