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# Prediction of T-year flood in gauged and partially gauged small catchments

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## Introduction

Flood flows having given recurrence intervals or probabilities of exceedance, i.e. the design flows, are basic hydrological information required in designing culverts, bridges and other hydraulic structures as well in assessing flood risk managements. The last one is especially important because of the current implementation of the EU "Flood Directive" (Majewski 2006; Klijn et al. 2008). The purpose of the Directive is primarily to document flood risks and improve the flood prognosis. The flood predictions are equally important for large and small rivers and need to be determined for gauged and ungauged locations. Whereas in case of larger rivers, which have long term monitoring data, the procedures of flood frequency estimation are commonly accepted, in case of small rivers, usually ungauged the procedures have usually high degree of uncertainty (Banasik et al. 2003; Aronica et al. 2004). In this chapter, estimation of T-year floods for two small catchments, of which one has long term, i.e. 48-year flow data and the other one only short term, i.e. 2.5-year monitoring record, is presented.

## Location and main parameters of the two catchments

These two catchments are the Zagożdżonka River and the Zwoleńka River. The first one has been gauged at Płachty since summer of 1962, so 48 year flood data (1963–2010) are available for flood frequency analysis, and the other one was monitored at Siekierka gauge for two and half years (since July 2008 until December 2010). They are located in central part of Poland, ca 100–130 km south of Warsaw (Figure 3.1). The catchments bordered to each other and both rivers are left tributary to the Vistula

River, with outlets at its middle reach. Mean annual precipitation is ca 610 mm and mean annual runoff is in the range of 106–110 mm. The month with the highest precipitation (of ca 79 mm, i.e. 12.9% of annual value) is July, and the month with the highest runoff depth (of ca 15.5 mm, i.e. ca 14.7% of annual value) is March. More detailed description of the both catchments is presented in chapter 1.

Main characteristics of the catchment of the Zagożdżonka River at Płachty gauge and on the Zwoleńka River at Siekierka gauge are given in Table 3.1. The area of the catchments are: 82.4 $km^2$ and 186.8 $km^2$, for the first and the other one, respectively. Main channel of the Zagożdżonka River is a bit steeper (on average ca 2.37‰) then the one of the Zwoleńka River (1.63‰). However, both are classified as lowland rivers. Shape factor, characterizing the process of flood formation, and defined as the drainage area divided by the square of the main channel length is 0.60 for Zagożdżonka and 0.29 for Zwoleńka. There are also differences in soil of the river valley as well as in the river channel plan. In case of the Zagożdżonka River there is mainly narrow valley with straight river channel, and in case of the Zwoleńka River the valley is wider, often up to 200–500 m, with peat soils, and often meandering stream. The river gauging sites of both rivers are shown on Figure 3.2 and 3.3.

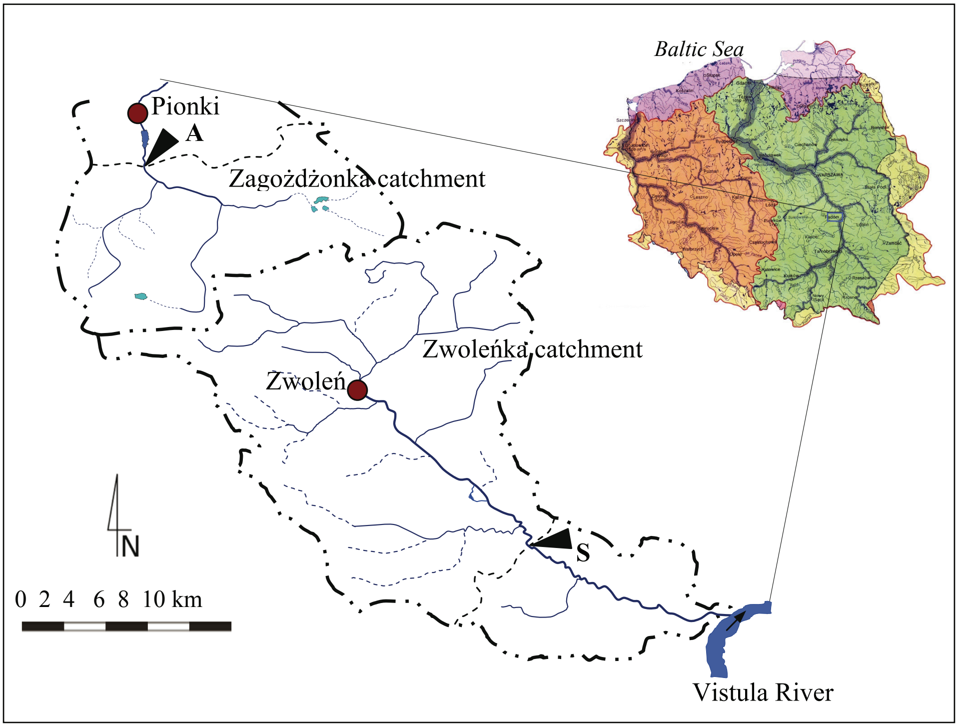


FIGURE 3.1. Locality map of Zagożdżonka catchment, with the river gauge Płachty (A) and Zwoleńka catchment, with the river gauge Siekierka (S)

TABLE 3.1. Main characteristics of the analyzed catchments

| No | Category | Zagożdżonka River at Płachty gauge | Zwoleńka River at Siekierka gauge |
|---|---|---|---|
| 1 | Area – A ($km^2$) | 82.4 | 186.8 |
| 2 | Length of the main river – L (km) | 11.7 | 25.2 |
| 3 | Main river slope – J (m/km) | 2.37 | 1.63 |
| 4 | Mean catchment slope – Ψ (m/km) | 4,08 | 3,66 |
| 5 | Shape factor SH defined as the drainage area divided by the square of the main channel length – $A/L^2$ (–) | 0.60 | 0.29 |
| 6 | Ratio of forest area (–) | 0.40 | 0.24 |
| 7 | Width and soil of the river valley, river channel plan | narrow valley with organic soils, usually straight river channel | wide valley (up to 200–400 m), with organic & peat soils, often meandering river, specially in its lower reaches |
| 8 | Continuous discharge record | Long term (48 years) | Short term (2,5 years) |
| 9 | Gauging cross section | channel | bridge |


FIGURE 3.2. The Zagożdżonka River at Płachty gauge


FIGURE 3.3. The Zwoleńka River at Siekierka gauge

# Estimation of T-year flood in gauged catchment of the Zagożdżonka River

The problem of estimating flood flows has an increasing importance in various environmental studies (Cunderlink et al. 2006; Cyberski et al. 2006, Pinter et al. 2006; Bogdanowicz 2010; Strupczewski & Kochanek 2010). In small catchment, where long term records are not available, this is usually done with the use of mathematical modeling or in the same engineering cases, with the use of empirical methods. Both however should be verified by comparing the estimates with results of statistical methods, when the recorded data are available.

Some preliminary investigation on flood frequency analysis for this river has been carried out earlier with the use of shorter set of data (Banasik et al. 2003; Banasik and Byczkowski 2006 and 2007). In this case two approaches are applied for analysis of the flood flow data collected in the period 1963–2010. The first one, as recommended by Guidelines for Flood Frequency Analysis (IMWM 2005), is based on two separate series of floods, which are formed from maximum annual winter season floods i.e. caused by snowmelt, and maximum annual summer season floods, i.e. caused by rainfall (WS-M). The other approach is the traditional one, which does not take flood genesis into account and statistical series is formed from the annual maximum (AM) flows of hydrological years. The flood data used for both approaches i.e. WS-M and AM are presented on Figures 3.4 and 3.5, respectively.

A computer program, using four types of probability distribution functions (gamma, log-normal, Weibull and log-gamma), and developed at IMWM (2005) by Ozga-Zielińska et al. (1999), was applied for frequency analysis with the use of AM and WS-M series, respectively.

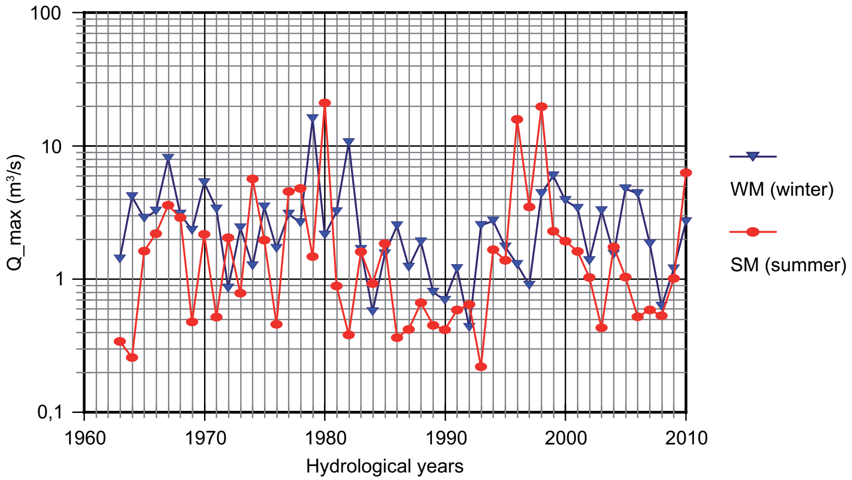


FIGURE 3.4. Maximum annual winter season (snowmelt) floods and maximum annual summer season (rainfall) floods

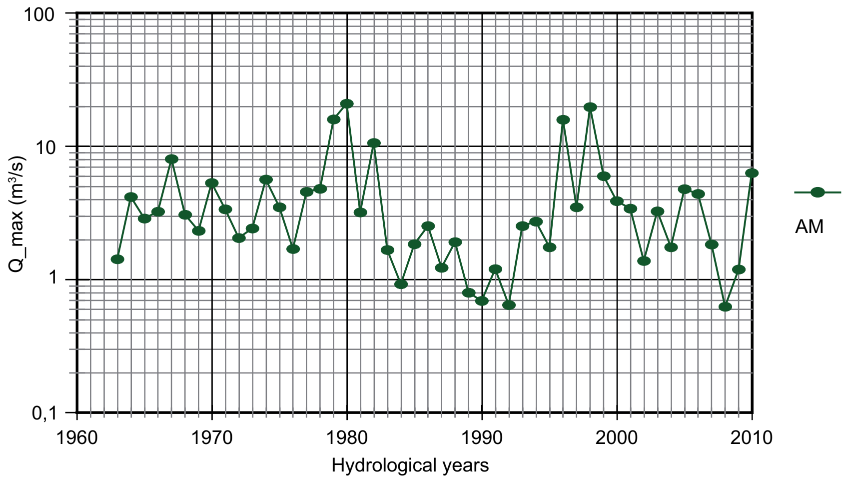


FIGURE 3.5. Annual maximum (AM) flood flows of hydrological years

The process of performing the frequency analysis with the use of the computer program is being conducted after prior examination of the homogeneity of the series with the use of statistical methods. The methods included:

a) investigation of the outliers with the use of Grubbs-Beck test,
b) investigation of the independence of elements of the sample with the use of the run test,
c) investigation of the stationarity of the series with the use of the three following tests:
   - the Kruskal-Wallis one-way analysis of variance by ranks,
   - the Spearman test for trend of mean value,
   - the Spearman test for trend of variance.

The examination of the homogeneity of both sets of data, i.e. WS-M and AM, showed that the 48-year series fulfilled all of the conditions of homogeneity at 0.05 significance level. The problem of accepting the series to, or rejecting it from the frequency analysis, depending on the fulfilling the respective homogeneity criteria, has been also discussed by Węglarczyk (2007) and Ozga-Zielińska et al. (2007).

Having applied the Akaike criterion (Mutua 1994), the log-normal statistical distribution has been indicated for winter and summer floods as best fitted to the measured values. However, the Weibull statistical distribution was a bit better then log-normal one, according to Akaike criterion, when annual series (AM) were analyzed. Results of the flood frequency analysis for the log-normal distributions are presented on Figures 3.6 and 3.7, as well as in Table 3.2. Comparison of the results of annual

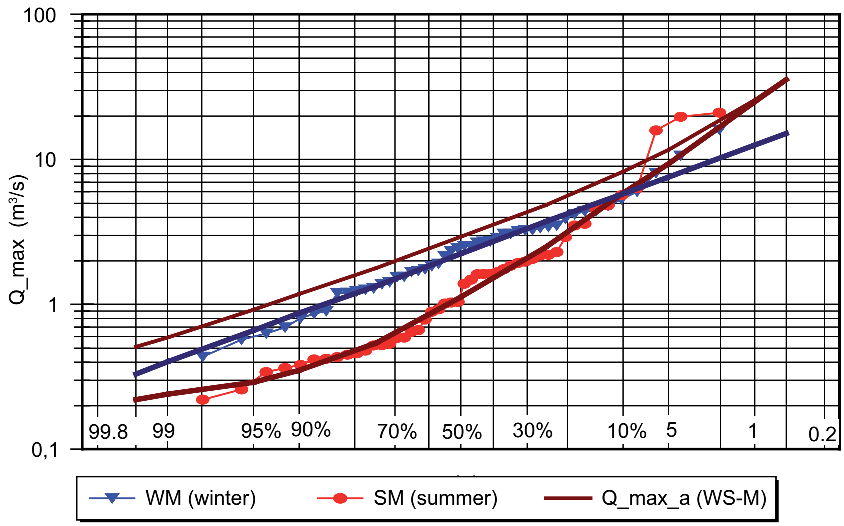


FIGURE 3.6. Seasonal Flood Frequency Curve for Zagożdżonka catchment compared with observed values (WM – winter floods, SM – summer floods, WS-M – annual frequency curve computed according to function of alternative)

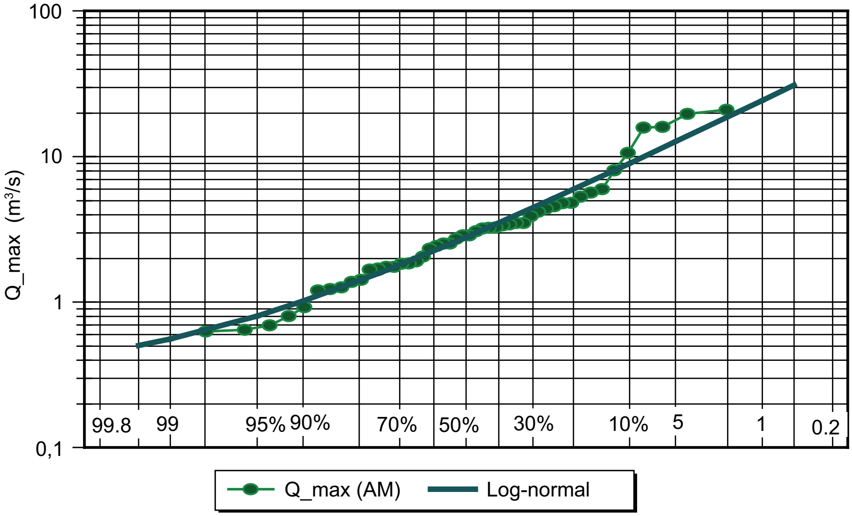


FIGURE 3.7. Annual Flood Frequency Curve for Zagożdżonka catchment compared with observed values

TABLE 3.2. Seasonal and annual food flows in the Zagożdżonka River at Płachty gauge based on the 48-year-series (1963–2010)

| Return period<br>T (years) | Proba-bility<br>**p** (%)<br>(1-CDF) | Seasonal and annual flood flows $\boldsymbol{Q}_{max\_p}$ (m³/s) estimated on the basis of: | | | | Relative difference |
|---|---|---|---|---|---|---|
| | | seasonal series | | | annual series (AM) | $\frac{Q^{AM}_{max\_p} - Q^{WS-M}_{max\_p}}{Q^{WS-M}_{max\_p}}$ |
| | | winter floods (WM) | summer floods (SM) | annual floods (WS-M) | | |
| Function accepted ===> | | log-normal | log-normal | function of alternative | log-normal | (%) |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 1000 | 0.1 | 22.0 | 73.3 | 73.3 | 50.9 | –30.6 |
| 500 | 0.2 | 18.8 | 54.3 | 54.3 | 41.1 | –23.7 |
| 200 | 0.5 | 15.0 | 35.5 | 35.8 | 30.9 | –13.5 |
| 100 | 1.0 | 12.5 | 25.0 | 25.6 | 24.3 | –5.11 |
| 20 | 5.0 | 7.55 | 9.32 | 11.6 | 12.7 | 9.01 |
| 10 | 10 | 5.77 | 5.84 | 8.21 | 8.98 | 9.40 |
| 2 | 50 | 2.23 | 1.12 | 2.93 | 2.79 | –4.72 |
| Mean $\boldsymbol{Q}_{max}$ | | 2.97 | 2.65 | X | 4.33 | X |

flood frequencies estimated according to Weibull distribution and log-normal one was conducted on the base of 46-year flood data of this catchment by Banasik and Byczkowski (2010). So for analyzing the AM series also log-normal distribution has been selected in this study.

The results presented on Figures 3.6 and 3.7 and in Table 3.2 indicate that:

- there is evident difference in shape (slope) of flood frequency curve (FFC) for winter (snowmelt and rainfall-snowmelt) floods and summer (rainfall) floods (Figure 3.6). The computed skewness coefficient has been 2.89 for the winter series and 3.15 for the summer one, so at the mean values of 2.97 $m^3/s$ and 2.65 $m^3/s$ for winter and summer events respectively, the flood flows based on winter maximum discharges are larger than computed for summer series for the higher probability of exceedance (i.e. here for $p > 10\%$). For the low probability of exceedance (i.e. here for $p < 10\%$ the) summer floods are larger than the winter events,
- there are relative small differences (below 10%) between FFCs estimated on the base seasonal maximum discharges (WS-M) and annual maximum discharges (AM) for probability of exceedance of ca 1% and higher. For probability of exceedance 0.5% and lower the differences are increasing, i.e. FFC based on seasonal series is producing higher flood flows evidently. Taking into account various geneses of the flood events during winter and summer seasons and the presented results, the annual floods of given probability of exceedance should be computed as function of alternative from seasonal flood frequency curves.

Applying indirect methods based on an index flood estimated on shorter periods (i.e. 10 year series) or respective specific index flood flow and catchment area, and on regional quantiles distribution (Stachy and Fal 1986; IMWM 1987; Byczkowski 1999) in previous study, Banasik et al. (2003) received evident disagreement in estimated floods with results produced by the direct (statistical) method. This is why an attempt for estimating flood flows in partially gauged catchment has been undertaken (Banasik and Byczkowski 2011).

## Estimation of T-year flood in partially gauged catchment of the Zwoleńka River

An index flood represents the typical magnitude of flood expected at given site (WMO 1994; Kjeldsen & Rosbjerg 2002). In methodology of IMWM (Stachy and Fal 1986) and also in Flood Estimation Handbook (CHE, 2008), the median annual maximum flood is adopted as the index flood. So the index flood for the gauged site (the Zagożdżonka River at Płachty site) is $Q_{max,50\%} = 2.93$ $m^3/s$ (Table 3.2, penultimate row, column 5). Relationship between corresponding discharges of the Zagożdżonka River at Płachty gauge (donor site) and the Zwoleńka River at Siekierka gauge (subject site) have been estimated on the base of two group of data, the first one was 27 semi-simultaneous flow meter measurements and the other one was 14 peak hydrograph pairs (Figure 3.8). The data allowed finding a regression relationship in the form:

$$Q_{\text{Siekierka}} = 1.883 \cdot Q_{\text{Płachty}}^{0.788}$$

with coefficient of determination $r^2 = 0.91$.

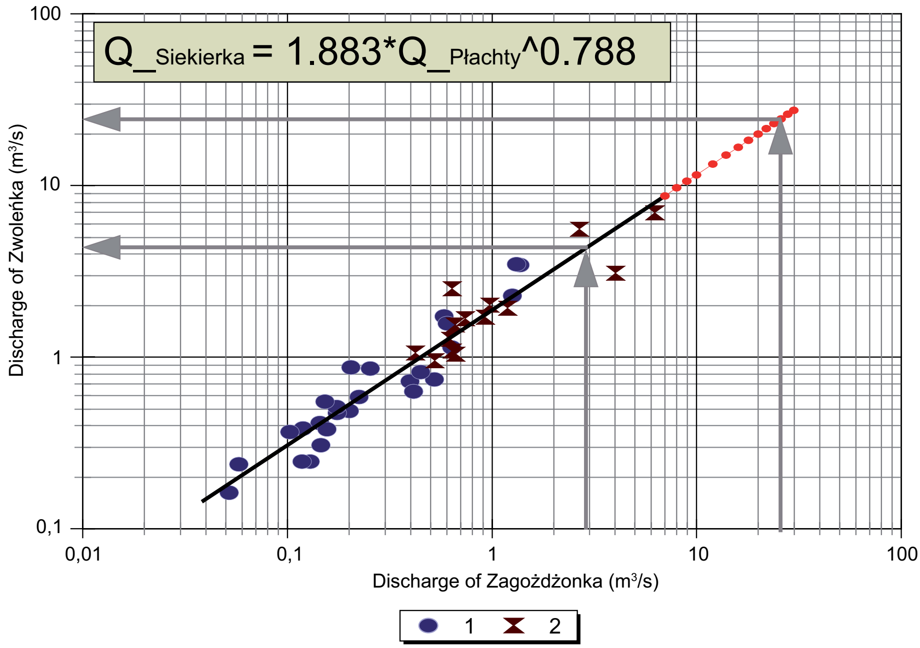


FIGURE 3.8. Corresponding discharges of the Zagożdżonka River at Płachty gauge and the Zwoleńka River at Siekierka gauge have been estimated on the base of semi-simultaneous flow meter measurements (1) and peak hydrograph records (2). Red dots represent the extrapolation of the regression relationship

Even the corresponding discharges are of two various origins; they are forming a homogeneous sample (Figure 3.8). The scope of the discharges at donor site range from 0.039 $m^3/s$ to 6.25 $m^3/s$, i.e. the upper value is much higher than index flood at donor site (ca. 2.13 times), so it allows to apply the regression relationship to estimate the index flood at subject site. In this way, flood flows of probability of exceedance of 10%, 5% and 1% have also been estimated; nevertheless they are in the extrapolated part of the relationship. The flood discharges for both sites, with respective specific discharges and with quantiles are given in Table 3.2. The quantiles $\mu_p$ are defined as:

$$\mu_p = \frac{Q_{\max,\, p\%}}{Q_{\max,\, 50\%}} \tag{2}$$

where:

$\mu_p$ – quantiles for the gauging station of region (–),
$Q_{max,\,50\%}$ – two year flood flow assumed as index flood (m$^3$/s),
$Q_{max,\,p\%}$ – flood flow with probability of exceedance o p% (m$^3$/s).

For comparison purposes also respective quantiles estimated for the region by Stachy and Fal (1986) have been given in Table 3.3 (column 9).

TABLE 3.3. Comparison of flood discharges for the Zagożdżonka River at Płachty with the Zwoleńka River at Siekierka and the quantiles for both rivers

| Return period T (years) | Probability $p$ (%) (1-CDF) | Flood discharges $Q_{max,\,p\%}$ (m$^3$/s) | | Specific discharge $q_{max,\,p\%}$ (dm$^3$/s/km$^2$) | | Flood quantiles $\mu_p$ (–) | | |
|---|---|---|---|---|---|---|---|---|
| | | at Płachty | at Siekierka | at Płachty | at Siekierka | at Płachty | at Siekierka | for the region* |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 100 | 1 | 25.6 | 24.3 | 311 | 130 | 8.75 | 5.52 | 4.30 |
| 20 | 5 | 11.6 | 13.0 | 141 | 69.6 | 3.97 | 2.96 | 2.98 |
| 10 | 10 | 8.21 | 9.89 | 99.6 | 53.0 | 2.80 | 2.25 | 2.40 |
| 2 | 50 | 2.93 | 4.39 | 35.6 | 23.5 | 1.00 | 1.00 | 1.00 |

* Stachy & Fal 1986; Byczkowski 1999.

## Comparison of the results and concluding remarks

With reference to the chapter 1, in which flow duration curves (FDCs) was considered; it has been evident that specific discharges (outflow of water from catchment unit area) for long duration (i.e. 20 and more percent of time the flow is exceeded) were higher for the Zwoleńka River than for the Zagożdżonka River. Then with increasing discharges the differences decreased, so for higher computed flow (i.e. for 10 and less percent of time the flow is exceeded), the ratio of specific discharge of Zwoleńka vs. Zagożdżonka became smaller then one, and finally for the largest computed specific discharge of 27.0 dm$^3$/s/km$^2$ at Płachty on Zagożdżonka River, i.e. for 0.5 percent of time the flow is exceeded, the ratio equaled 0.70. This trend, i.e. decrease of the ratio of specific discharges with increase of the flood discharges is continued also for the maximum probable flow values as presented in Table 3.3 (columns 5 & 6) and in Table 3.4 (columns 3).

Before accepting the results of estimation it would be worth to reconsider the steps which lead to find the results.

Firstly FFC for the gauge catchment, i.e. the Zagożdżonka River at Płachty gauging station, has been estimated on the base of good quality date. The rating curve has been verified each year on the base of 8–12 new flow meter measurements. For many recent years two independent teams conducted the hydrometric measurements, using independent instruments and calculating the discharge on the measured area-velocity data, individually. However, it is to point out that the highest discharge ever measured at Płachty was 4.33 m³/s on Sept. 1, 2010, at the larger one estimated from the water stage record and rating curve of 21.0 m³/s on Oct. 11, 1980. There were in total 15 larger events (eight in winter periods and seven in summer periods) than the maximal measured one, within the 96 values used for winter and summer FFCs estimation. The respective number of events larger twice than the maximal measured one was 5 (two in winter seasons and three in summer seasons). Nevertheless a lot of effort has been put for proper estimation the rating curves. It is also to point out that the maximal measured discharge was significantly higher the two-year flood for any of the presented series and was coinsidently equal to mean $Q_{max}$ of the AM serie (Table 3.2).

The index flood, i.e. $Q_{max,50\%}$, for both catchments could not be impeached. In case of the Zagożdżonka River, i.e. the donor site, there were very long series of recorded data and the index flood has been within the scope of hydrometric measured discharges. In case of the Zwoleńka River, i.e. the subject site there has been found a very strong relationship with the donor site.

Having the index floods for both sites, the flood quantiles, given in Table 3.3, and their ratios, given in Table 3.4, should be considered.

TABLE 3.4. Ratios of specific flood discharges and of flood quantiles for the considered catchments of Zagożdżonka and Zwoleńka

| Return period<br>T (years) | Probability<br>$p$ (%)<br>(1-CDF) | Ratio of specific flood discharges ($q_{max,\,p\%}$) of Zwoleńka vs Zagożdżonka | Ratio of flood quantiles ($\mu_p$) of two rivers at their gauging stations vs regional values | |
|---|---|---|---|---|
| | | | Zagożdżonka River at Płachty gauge | Zwoleńka River at Siekierka gauge |
| 1 | 2 | 3 | 4 | 5 |
| 100 | 1 | 0.42 | 2.03 | 1.28 |
| 20 | 5 | 0.50 | 1.33 | 0.99 |
| 10 | 10 | 0.53 | 1.17 | 0.94 |
| 2 | 50 | 0.66 | 1.00 | 1.00 |

The data in Tables 3.3 and 3.4 indicate that:

- the Zwoleńka River has lower specific flood discharges than the Zagożdżonka River (Table 3.3, columns 5 & 6). The ratio of the specific flood discharges of the Zwoleńka vs. the Zagożdżonka River decreases from 0.66, at the return period for 2-year flood, to 0.42 for 100-year flood (Table 3.4, column 3),
- Flood quantiles for the Zwoleńka River increase slower with flood return period than for the Zagożdżonka River (Table 3.3, columns 7 & 8). The ratio of the site specific quantiles to regional ones (Table 3.4, columns 4 & 5) indicate that Zwoleńka has flood characteristic close to typical river for the region, while Zagożdżonka seems to be more "wild" river.

Lower specific flood discharges and lower values of flood quantiles, as found out for the Zwoleńka River, is typical for larger catchments. In this case however, there might have been also other more influential reasons of the difference as: meandering channel in a wide valley of organic soils, lower river channel slop and elongated shape (lower shape factor) of the Zwolenka catchment.

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