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Thermal and snow conditions of winters and winter floods on example of Zagożdżonka River

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Abstract: *Thermal and snow conditions of winters and winter floods on example of Zagożdżonka River.* Thermal and snowy conditions in Zagożdżonka River catchment during hydrological years 2003–2013 and winter floods are presented in paper. The meteorological and hydrological data, such as maximum, minimum, mean diurnal air temperatures, daily snow cover depth, and water discharge, collected at Czarna station (WULS-SGGW) have been used. Meteorological conditions were analyzed using indexes proposed by Paczos. Temperate cold and extraordinarily low snowy winters has dominated in Zagożdżonka catchment in presented period of time. Winter floods as a result of snowmelt have been observed almost each year, except 2008 when winter was mild and extremely low snowy. The relation between winter severity index (WO_2) and winter snowiness index (WS_n) has been estimated, as well as the relation between winter snowiness index and maximum discharge (Q_{max}).

Key words: winter severity, winter snowiness, winter floods

INTRODUCTION

The climate warming has been registered in both, the global (Kundzewicz 2008, 2011) and local scale (Kozuchowski, Żmudzka 2001; Marsz, 2005; Kundzewicz, Kozyra 2011). Those works indicated a multidirectional changes of thermal conditions in the various months of the year for last 30 years. It is confirmed

that the temperature of January, February and March has increased. It is also expected, that the spring runoff will be reduced, due to the increasing temperature and decreasing snow cover and precipitation (Piętka 2009).

Thermal and snowiness classification of winters is difficult, because the climate, weather and the winters in Poland diverse in a wide range. Published works relate to the thermal conditions (Piotrowicz 2002; Biniak-Pieróg et al. 2012; Grabowski et al. 2013) or snow cover (Chrzanowski 1988; Nowosad, Bartoszek 2007; Wojkowski 2009; Wojkowski, Partyka, 2009; Czarnecka 2011, 2012). The problem of both, thermal and snowy conditions of winters and in particular the occurrence of extremely cold and snowy or extremely mild and low snowy winters recently have been the subject of regional investigations carried out by Janasz (2000), Olba-Zięty, Grabowski (2007), Majewski et al. (2011). Studies in Poland scale have been carried out by Paczos (1982, 1985) and recently by Ziernicka-Wojtaszek (2013). Paczos (1982) have found the dependencies between winter severity and snowiness indexes. The other cited authors confirmed this relation, based on the collected data

from different parts of Poland. However there are not much investigations, which describe the relation between winter conditions and floods caused by snowmelt on the lowland areas. Therefore the scope of this paper is an estimation of relation between chosen meteorological condition in a form of winter snowiness index and winter severity index, their relation and changeability during years as well as relation between those indexes and runoff. All analysis has been carried based on the data collection from small catchment in the middle part of Poland.

MATERIAL AND METHODS

Study catchment

The investigation was based on the data collected by the Department of Hydraulic Engineering, Warsaw University of Life Sciences – SGGW, from the 23.4 km² lowland catchment of Zagożdżonka

River at the Czarna gauging station. Located in central Poland (Fig. 1) Zagożdżonka River is a left tributary of Vistula River. The catchment area, which contributes to direct runoff (without local depressions) to river system is 19.6 km², upstream of Czarna gauge (shown as B in Fig. 1). Absolute relief is 26.5 m in this subcatchment. The mean slopes of main streams are from 2.5 to 3.5 m per 1000 m (Hejduk, Banasik 2010a).

Sandy soils (from almost pure to loamy sands), which covered 90% of watershed to Czarna gauging station are the main type of soils. In local depressions and river flood plains peaty soils may be found. Land use in the watershed upstream of Czarna gauge is dominated by arable land – 70% of total area; 20% of area is covered by forest, 9.4% is pastures and 0.6% is paved areas.

According to Banasik et al. (2013), the mean annual precipitation and run-

FIGURE 1. Locality map of the watershed

off for Zagożdżonka catchment from the period 1963–2011 are estimated at 612 mm (range: 941 mm in 1974 – 414 mm in 1991) and 107 mm respectively (range: 209 mm in 1980 – 52 mm in 1992). The month with the highest rainfall (average 81.8 mm) is July, while the precipitation in January is the lowest in the year (31.7 mm). The month which is the most abundant in water is March, while the most dry is July (Banasik et al. 2013). Average precipitation in winter season for hydrological years 2003–2013 was 215 mm, with range of 166–258 mm. According to rainfall distribution in presented period of time, the driest one was April (32.6 mm). The rest of months of winter season had similar amount of precipitation.

Since hydrological year 2003 snow cover depth and water equivalent at Czarna is measured. The snow cover usually appears between 25–30 of November and disappears between 20–25 of March. The snowmelt period is usually 1–4 days long (Hejduk 2009).

The average discharge of the years 1991–2010 for Zagożdżonka River till Czarna gauging station is $0.071 \text{ m}^3/\text{s}$ (Hejduk 2011a). Two-year-flood discharge ($WQ_{50\%}$) equals $1.04 \text{ m}^3/\text{s}$ (Hejduk, Banasik 2010a). The mean annual suspended sediment concentration (SSC) is low and has been estimated for 14 mg/l (Hejduk 2001; Hejduk et al. 2010), however for snowmelt floods it has been estimated for 19.5 mg/l (Hejduk, Banasik 2010a). Yearly total sediment yield from Czarna station is about 60 Mg (Banasik 1983). Winter floods in Zagożdżonka River are in most cases snowmelt-rain-

fall one. They can provide the biggest amount of suspended sediment during hydrological year.

Measurements

All calculations were based on the data collected at Czarna gauging station. Air temperature and water level were measured using an electronic equipment with 10 minutes time step (Hejduk et al. 2010; Hejduk, Deelstra 2011). The discharge has been estimated based on hydraulic rating curve for sharp-crested weir (Hejduk, Banasik 2010b), which has been verified using hydrometric measurements, taken several times during hydrological year. Discharge and precipitation allowed to determine the hydrograph of winter flows and identify winter floods. The snow cover depth has been measured at least once a day at 7 a.m. using lowland type of Chomicz's weight snow-sampler (Janiszewski 1988; Hejduk 2009). In case of intensive snowfall the measurement were taken few times a day according to IMGW standards (Janiszewski 1988). The measurement allows to determine snow water equivalent too.

The daily hydrograph, observations of snow cover, temperature and precipitations allowed to determined snowmelt periods and floods. The data of air temperature and snow cover depth has been used to calculate winter severity and snowiness indexes.

Calculations of winter severity index and snowiness index

Within the meaning of meteorological season, the winter is usually describe as a period between December 1st and

February 28th or 29th. In Poland March and beginning of April are very often characterized by the weather conditions typical for winter season, such as air temperature below 0°C and the snow cover. According to hydrological year (from November 1st to October 31st the next year) winter season is a period between November 1st and April 30th. This is a time, when the meteorological conditions are typical for autumn, winter and early spring.

Paczos (1982) has analyzed the data set from several meteorological stations, which were representative for the different regions of Poland. He has calculated selected thermal and snow characteristics. Based on these analyses, as a winter period he has adopted the time from December 1st till the end of March and proposed the method of calculation the winter severity and snowiness indexes. In this methodology winter severity index is determined based on temperature's characteristics of winter season and winter snowiness index is calculated based on snow cover depth.

Winter severity has been determined by using numerical index proposed by Paczos (1982), modified by Janasz (2000), computed from the following empirical formula:

$$WO_z = (1 - 0.25 \cdot t) \cdot 0.8325 + 0.0144 \cdot d_z + 0.0087 \cdot d_m + 0.0045 \cdot d_{bm} - 0.0026 \cdot S_t \quad (1)$$

where:

WO_z – winter severity index, from 0 – the mildest winter, to 10 – the most severe winter (-),

t – average temperature of the winter season (°C),

d_z – the number of winter days, average daily temperature, $t_a < 0^\circ\text{C}$,

d_m – the number of frosty days, $t_{\max} < 0^\circ\text{C}$,

d_{bm} – the number of very frosty days, $t_{\max} < -10^\circ\text{C}$,

S_t – the sum of average daily air temperature below 0°C,

Winter snowiness index, has been calculated also from Paczos' formula:

$$WS_n = 0.0409 \cdot d_{ps} + 0.0246 \cdot d_{ps20} + 0.00007 \cdot S_h \quad (2)$$

where:

WS_n – winter snowiness index, from 0 to 10 (-),

d_{ps} – the number of days with snow cover depth above 1 cm,

d_{ps20} – the number of days with snow cover depth above 20 cm,

S_h – the sum of total depth of snow in the winter season (cm).

According to Chrzanowski's (1988) classification, the snow cover depth between 20 and 40 cm is recognize as thick one. Based on calculated indexes of thermal and snowiness, Paczos (1982) has estimated ten types of thermal and snowy characteristics of winter (Table 1).

TABLE 1. Types of winter severity and snowiness by Paczos (1982)

Winter severity			Winter snowiness		
Type	WO_z	Thermal classification	Type	WS_n	Snowiness classification
I	0.01–1.00	very mild	I	0.01–1.00	extremely low snowy
II	1.01–2.00	mild	II	1.01–2.00	extraordinary low snowy
III	2.01–3.00	temperate mild	III	2.01–3.00	very low snowy
IV	3.01–4.00	temperate cold	IV	3.01–4.00	temperate low snowy
V	4.01–5.00	cold	V	4.01–5.00	low snowy
VI	5.01–6.00	temperate severe	VI	5.01–6.00	temperate snowy
VII	6.01–7.00	severe	VII	6.01–7.00	snowy
VIII	7.01–8.00	very severe	VIII	7.01–8.00	very snowy
IX	8.01–9.00	extraordinary severe	IX	8.01–9.00	extraordinary snowy
X	9.01–10.00	extremely severe	X	9.01–10.00	extremely snowy

RESULTS AND DISCUSSION

Thermal characteristic and snow cover of considered time period

The average air temperature in the winter season (XI–IV) of hydrological years 2003–2013 at Czarna station (Table 2) ranged from 3.6 to -1.2°C with a standard deviation of 1.2°C . Warmest months are November and April with the monthly average air temperature of 4.3 and 8.4°C respectively. The coldest months are January and February with an average temperature of -2.9 and -2.6°C respectively.

The winter season of 2007 was the warmest one with an average air temperature of 3.6°C , while the coldest winter has been observed in hydrological year 2006 with an average air temperature of -1.2°C . The lowest air temperature

(-32°C) at Czarna station in 2006 has been recorded on January 23rd and 24th. The air temperatures below 0°C persisted throughout January and February and the most of March.

The snow cover has been observed in each year of 2003–2013 (Fig. 2). 11-years average total number of days with snow cover was 67, which is close to average for this region of Poland. Chrzanowski (1988) has estimated the total number of days with snow cover equal to 70 for central part of Poland. There was the low number of days with snow cover above 20 cm observed (average 11 days) almost each year, except 2006 and 2010 (57 and 39 days respectively). The decreasing number of days with thick snow cover suggests changes in thermal regime of winters and confirms warming of this season.

TABLE 2. The average air temperature, winter severity index (WO_z) and snowiness index (WS_n) at Czarna station during hydrological years 2003–2013

Hydrological year	Average air temperature (°C)								WO_z (-)	WS_n (-)
	XI	XII	I	II	III	IV	XI–IV	XII–III		
2003	4.3	−6.0	−2.9	−5.4	2.2	7.4	−0.1	−3.0	4.3	1.8
2004	6.5	0.1	−5.4	−1.0	2.2	7.0	1.6	−1.0	3.2	2.9
2005	3.1	1.3	−0.4	−4.4	−0.9	8.0	1.1	−1.1	3.1	2.5
2006	2.3	−1.3	−9.8	−4.3	−1.8	8.0	−1.2	−4.3	5.2	6.1
2007	4.8	2.6	2.6	−1.6	5.6	7.5	3.6	2.3	1.1	1.2
2008	0.6	−1.3	0.3	2.0	2.6	8.3	2.1	0.9	1.8	0.3
2009	5.0	1.2	−3.1	−0.9	2.2	9.7	2.4	−0.2	2.4	1.7
2010	5.6	−0.9	−8.2	−1.6	3.5	9.1	1.3	−1.8	4.0	3.7
2011	6.9	−5.5	−0.7	−4.2	3.0	10.1	1.6	−1.8	3.7	3.8
2012	2.4	2.4	−1.2	−6.7	4.3	9.6	1.8	−0.3	2.6	1.3
2013	5.6	−2.9	−3.3	−0.6	−1.9	8.1	0.8	−2.2	3.9	3.4
Average	4.3	−0.9	−2.9	−2.6	1.9	8.4	1.4	−1.1	3.2	2.6
Maximum	6.9	2.6	2.6	2.0	5.6	10.1	3.6	2.3	5.2	6.1
Minimum	0.6	−6.0	−9.8	−6.7	−1.9	7.0	−1.2	−4.3	1.1	0.3
Standard deviation	2.0	3.0	3.7	2.6	2.4	1.1	1.2	1.8	1.2	1.6

FIGURE 2. The number of days with snow cover

Winter severity and snowiness

Both, winter severity and snowiness indexes have been calculated for the period from December to March. The value of winter severity index (WO_z) ranged from 5.2 to 1.1 with a standard deviation

1.2. In the analyzed period, four types of winter severity (Table 3) have been observed: mild winter occurred twice (II), as well as temperate mild winter (III). Four times temperate cold winter (IV) was observed. Once temperate severe

TABLE 3. Thermal and snowiness classification of winters 2003–2013

Winter	Type	Thermal classification	Type	Snowiness classification
2002/2003	V	cold	II	extraordinarily low snowy
2003/2004	IV	temperate cold	III	very low snowy
2004/2005	IV	temperate cold	III	very low snowy
2005/2006	VI	temperate severe	VII	snowy
2006/2007	II	mild	II	extraordinarily low snowy
2007/2008	II	mild	I	extremely low snowy
2008/2009	III	temperate mild	II	extraordinarily low snowy
2009/2010	IV	temperate mild	IV	temperate low snowy
2010/2011	IV	temperate cold	IV	temperate low snowy
2011/2012	III	temperate mild	II	extraordinarily low snowy
2012/2013	IV	temperate cold	IV	temperate low snowy
Average		temperate cold		extraordinarily low snowy

winter (VI) occurred, and at the same time it was the most snowy winter (VII) in analyzed period of time. Because of short period of investigations, it is difficult to estimate the tendencies in winter severity. During first four years of research, cold, temperate cold and temperate severe winters occurred. Mild and temperate mild winters have been recorded five times during last seven years. After winter 2005/2006 there was no winter with thermal type higher than IV.

Winter snowiness index ranged from 6.1 to 0.3 with a standard deviation 1.6. In two of the four cases of temperate cold winter, the season was very low snowy (III), in two others temperate low snowy (IV). In 2007 and 2008 winters were mild but in 2007 extraordinarily low snowy (II) and in 2008 extremely low snowy (I). Winters of 2009 and 2012 were classified as temperate cold

but also extraordinarily low snowy (II). Similar to winter serenity, after winter 2005/2006 there was no winter with snowiness type higher than IV

Winter severity index and winter snowiness index relation

There is a significant statistical correlation between winter severity index – WO_z and winter snowiness index – WS_n (Fig. 3), with the correlation index $R = 0.83$, $\alpha = 0.05$. Similar relation were observed by other researchers. Paczos (1982) received correlation coefficient between WO_z and WS_n equal to 0.88 for Poland, Majewski et al. (2011) for WULS-SGGW meteorological station received correlation coefficient equal to 0.79, Olba-Zięty and Grabowski (2007) for Biebrza Valley equal to 0.71. It means that along with the progressive warming, the number of days with snow cover will be reduced. The requirement

FIGURE 3. The relationship between snowiness index and thermal severity index in Zagożdżonka catchment in 2002/2003–2012/2013

for the snow cover formation is a moderate or heavy snowfall, which creates and strengthens the snow cover. Low air temperature is a factor in the formation and maintenance of snow cover. The snow cover will exist as long as air temperature will be respectively low. This explains the correlation between WO_z and WS_n .

Maximum water discharge and winter snowiness index relation

During 2003–2013 hydrological years winter floods as a result of snowmelt have been observed almost each year. Table 4 shows basic characteristic of snowmelt floods during this period. The peak of winter floods of 2003, 2005, 2006, 2010, 2011 and 2013 at least once during the season was about two-year-flood or higher.

The biggest snowmelt flood was recorded in March 2005, when the winter was temperate cold and very low snowy. The flood was the result of rapid snowmelt with very small amount of rain. The maximum discharge of this event was 3.444 m³/s, which was three times more than two-year-flood discharge. The volume of the flood ($V = 316.3 \cdot 10^3$ m³) was 14.6% of total runoff (total runoff of 2005 was equal to $2,172.4 \cdot 10^3$ m³). This flood transported 14.02 Mg of sediment, which was 23.4% of total annual sediment yield. The second biggest snowmelt flood was observed in March 2006 with maximum discharge of 2.781 m³/s and the volume of $295.7 \cdot 10^3$ m³, which was 15.6% of total runoff (total runoff of 2006 was equal to $1,892.2 \cdot 10^3$ m³). The mass of suspended sediment transported during this event was 10.43 Mg (17.4% of total annual sediment yield).

TABLE 4. General characteristic of collected snowmelt events of Zagożdżonka River at Czarna station

Category	Range
Maximum discharge, $Q_{\max}$ (m ³ /s)	0.144–3.444
Average discharge, Q_a (m ³ /s)	0.090–1.268
Volume of surface runoff, V_p (10 ³ m ³)	5.0–316.3
Total supply in snowmelt period (= melt + rainfall), MP (mm)	10.0–69.3
Effective supply, MP_{ef} (mm)	0.26–16.22
Sediment yield, M (Mg)	0.08–14.02
Average suspended sediment concentration, SSC_a (mg/l)	10.7–25.0

During winter time water is stored in accumulating snow cover. Few days long periods of warming can happen during the whole winter season, and cause the slowly melt of snow. Depending on air temperature, the snow cover may melt slowly or rapidly, when the long-term warming is coming. The high amount of accumulating snow, which melts rapidly, can generate higher runoff than that which would have been caused by rainfall in the same time (Makku et al. 2007). This has happened in winter 2005. The air temperature has been continuously low since the end of January till the middle of March. The few-days-long period of warming in February was too short to melt the snow. Accumulated snow cover has melted rapidly in March during the warm period, generated the high runoff and transported the high amount of sediment.

In 2006 low temperatures have been recorded since the end of January till the end of March, with few short periods of maximum temperature above 0°C. The warming period has come slowly. At first the snow cover has started to melt with no reaction from the catchment. Rapid increased of air temperature and rainfall in the same time caused the formation of flood.

In 2004, 2007, 2008, 2009 and 2012 the daily discharge of winter season was lower than 0.5 m³/s. In 2008, when the winter was mild and extremely low snowy, there was no reaction of the catchment on snowmelt. In fact there was no typical winter flood recorded as a consequence of snow thaw. The situation of 2012 was special too. Hydrological year 2012 was dry. November 2011 has been classified as extremely dry. The water storage in catchment at the beginning of winter season was small. The discharge of the whole winter season was low, even if it was higher than in summer half of the year. The winter was temperate cold and temperate low snowy. The temperature before snowmelt period was above 0°C, the soil was unfrozen. The reaction of the catchment on snowmelt was observed twice, the maximum of the discharge of each event was about 0.2 m³/s. Observed surface runoff was not high. In this case three parameters have been important: the water storage of catchment at the beginning of winter, thin snow cover (the amount of water accumulated in snow cover was low), and unfrozen soil (which has facilitated infiltration during snowmelt period). In February the streamflow drought

was observed in winter for the first time since the beginning of research. The summary of the discharge of Czarna station in winter seasons of 2003–2013 is given in Table 5.

TABLE 5. The average, maximum and minimum discharge at Czarna station, based on daily data set

Winter	The discharge of winter season XI–IV (m ³ /s)		
	$\underline{Q}_a$	$\underline{Q}_{\max}$	$\underline{Q}_{\min}$
2002/2003	0.087	1.09	0.035
2003/2004	0.079	0.341	0.031
2004/2005	0.091	2.023	0.033
2005/2006	0.088	1.678	0.025
2006/2007	0.092	0.497	0.036
2007/2008	0.055	0.215	0.024
2008/2009	0.071	0.329	0.019
2009/2010	0.114	1.009	0.006
2010/2011	0.197	1.259	0.034
2011/2012	0.066	0.233	0.007
2012/2013	0.116	1.251	0.030

The rapid snowmelt supplies the catchment and the water level increases. Low temperature has an impact on snow cover as well as snowmelt may have influence on the discharge. The relation between average and maximum discharge and snowiness index has been sought. There was no significant correlation between average discharge and snowiness but a significant statistical correlation ($R = 0.66$, $\alpha = 0.05$) between the maximum water discharge and the snowiness conditions has been found (Fig. 4). This relation indicate that the maximum discharge during winter could be connected with snowiness – if snowiness is higher the discharge caused by flood after melting of snow will be higher. However, data series of snow cover measurements for Zagożdżonka River are 11 years and it is still short period of time. For example, the point representing the winter season of hy-

FIGURE 4. The relation between winter snowiness index (WS_n) and maximum water discharge ($\underline{Q}_{\max}$) of winter season. $\blacktriangle$ represents $\underline{Q}_{\max}$ of 2005

drological year 2005 (marked as triangle in Fig. 4), stands out significantly from the remaining points. Taking into account that the winter flood recorded in March 2005 was on the top of extreme events in Zagożdżonka catchment, this situation was unusual, not typical even for winter season, when big floods happen. On the other hand, hydrological and meteorological processes in catchment scale are complicated and simple linear equation presented in this paper may not describe all snowmelt – runoff situations, so the research on the link between meteorological and hydrological parameters should be continued on longer data set.

CONCLUSIONS

1. According to the thermal and snowiness classification, temperate cold and extraordinarily low snowy winters has dominated in Zagożdżonka catchment during investigated period 2003–2013.
2. The most severe and snowy was winter 2005/2006. The most mild and in the same time extremely low snowy was winter 2007/2008.
3. The decreasing number of days with thick snow cover may suggests changes in thermal regime of winters.
4. There is a significant statistical relationship between winter snowiness index – WS_n and winter severity index – WO_z ($R = 0.83$, $\alpha = 0.05$). Based on this relation, along with the progressive warming, the number of days with snow cover will be reduced.

5. During 2003–2013 hydrological years winter floods as a result of snowmelt have been observed almost each year, except 2008 when winter was mild and extremely low snowy.
6. There is statistical significant relation between maximum water discharge and snowiness conditions ($R = 0.66$, $\alpha = 0.05$). The relation indicates that if the snowiness is higher the maximum discharge should be higher too.

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Streszczenie: *Warunki termiczne i śnieżne zim oraz wezbrania zimowe na przykładzie zlewni rzeki Zagożdżonki.* Wykorzystując wskaźniki ostrości termicznej i śnieżności zim według Paczosa, przedstawiono warunki termiczne i śnieżne zim na obszarze nizinnej zlewni rzeki Zagożdżonki oraz scharakteryzowano wezbrania zimowe, odnotowane w badanym okresie. Podstawowe dane meteorologiczne i hydrologiczne, takie jak temperatura powietrza (maksymalna, minimalna i średnia), grubość pokrywy śnieżnej, wysokość opadów, stany wody oraz zmęczenie wody w okresach zimowych lat hydrologicznych 2002-2013, pochodziły ze stacji pomiarowej SGGW zlokalizowanej w miejscowości Czarna, na obszarze badanej zlewni. W badanym okresie na obszarze zlewni Zagożdżonki dominowały zimy umiarkowanie chłodne i niezwykle małośnieżne. Niemal w każdym roku obserwowano wezbrania, których bezpośrednią przyczyną było topnienie śniegu. Wyjątek stanowił rok hydrologiczny 2008, kiedy zima była łagodna i ekstremalnie małośnieżna. Istnieje korelacja pomiędzy wskaźnikiem ostrości zimy a wskaźnikiem śnieżności.

Istnieje również zależność pomiędzy wskaźnikiem śnieżności a przepływem maksymalnym w okresie zimowym.

Słowa kluczowe: ostrość termiczna zim, śnieżność zim, wezbrania zimowe

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