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Surface water resources of small agricultural watershed in the Kujawy region, central Poland

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Abstract

The goal of the paper was to determine surface water resources of an agricultural watershed representative for the areas of intensive crop production in the Kujawy region. This area is characterised by the lowest average annual precipitation in Poland and high water demands related to the intensive crop production.

Hydrological studies were carried out in 2007–2011 in the upper Zgłowiączka River watershed located in the eastern part of the analysed region. Over 90% of the study area is used as an arable land.

Water velocity in the river bed and water level were measured at the outlet of the watershed in the river cross-section Samszyce.

The upper Zgłowiączka River has a snow-rainfall hydrological regime, strongly modified by anthropogenic activities related to the intensive crop production and installation of subsurface drainage system. The study period was characterised by very large temporal variability of hydrological conditions. The mean annual outflow coefficient amounted to 18% and varied highly in time: from 3% in the average years to 62% in the abnormally wet 2011. Average discharge (*SSQ*) in the Samszyce river cross-section was equal to 0.25 $m^3 \cdot s^{-1}$, and the mean unit outflow – to 3.2 $dm^3 \cdot s^{-1} \cdot km^{-2}$. The results of the study show that disposable surface water resources of the Kujawy region are very small, especially in the summer half-year. Thus, their utilization as a potential source of water for crop irrigation can be taken into account only, if water excesses will be retained within the watershed and used in conjunction with groundwater resources.

Key words: *climatic water balance, hydrological regime, outflow coefficient, the Kujawy region*

INTRODUCTION

Small research watersheds can be treated as outdoor laboratories for analysing and monitoring actual transformations in the environment resulting from human activities and climate change in a broad spectrum of variables. As local processes become more important with decrease in the area [BLÖSCHL *et al.* 2007], comparing to large river basins small catchments are particularly vulnerable to anthropogenic pressure. Thus, they are an excellent research base to study trends and changes in hydrological regime as well as ecosystem responses to land use changes and climate variability. This knowledge can be used by decision makers with respect to managing ecosystem services [IHP HWRP Germany 2013] and to develop local-based adaptation strategies to climate change and regional plans of water management. As human population will increase over the coming decades, managing ecosystems for services will become increasingly important to prevent e.g. shortages of water [KREMEN 2005]. Furthermore, monitoring of surface water resources in terms of quantity is necessary to determine availability of water, to verify norms of consumption (e.g. for irrigation) and to calculate the load of substances leaving the catchment.

In Poland only catchments of the size over 500 km^2 are covered by standard monitoring system of surface water carried out by the Institute of Meteorology and Water Management – National Research Institute (Polish abbreviation: IMGW-PIB). This system provides information about water balance and hydrological regime of large basins and rivers whereas surface water resources of small catchments remain unrecognised [KANOWNIK, KOWALIK 2010; SZYMCZAK 2005]. Understanding of hydrological regime is consistently one of the most important research problems due to continuous transformation of the environment as a result of anthropogenic pressure and impact of natural processes [OSTROWSKI, ZANIEWSKA 2001].

Forecasts suggest that in the following decades access to water resources will be probably one of the main reasons limiting development of agriculture all over the world [NILES *et al*. 2015; RIJSBERMAN 2006]. Some results show that water deficits have been the major constraint for the agricultural production in many regions on Earth since a long time ago [MIODUSZEWSKI 2006; POSTEL 1998]. As agriculture consumes 70% of the world's fresh water, farmers should be the primary target for incentives to conserve water [PIMENTEL *et al*. 2004]. In Polish agriculture limited water resources and low use efficiency are the main reason of problems related to water management [JANKOWIAK, BIEŃKOWSKI 2011].

The analysed Kujawy region belongs to these areas in Poland, which are particularly exposed to water deficits for crops [ŁABĘDZKI *et al*. 2002]. The region is characterised by the lowest annual sum of precipitation in the country and simultaneously by high water demands of intensive crop production. Determination of surface water resources of the Kujawy region is especially important due to periodic occurrence of water deficits in crop production, which has been noticed and described [HOHENDORF 1948] many decades before global warming and related natural hazards became a worldwide concern.

The results of the recent studies indicate an increasing trend of elements affecting evapotranspiration in Poland (air temperature and sunshine hours) [ŁABĘDZKI *et al*. 2014; SZWED 2015]. Increase of this factor may result in adverse changes in the structure of water balance of the analysed region which leads to decrease in water resources, particularly to lowering of groundwater depth and discharge in rivers [KĘDZIORA 2011]. All these changes may result in intensification of agricultural droughts. Water shortages will be the main barrier of further development of stable crop production, especially when unfavourable forecasts of climate change for the Kujawy region (air temperature increase and decrease in precipitation during a growing season) will come true.

A limited number of papers have been published up to now in the field of hydrology and water resources of the Kujawy region [BARTCZAK 2007; BARTCZAK *et al*. 2014]. Thus, the goal of the paper was to: analyses water balance and determine surface water resources of the agricultural watershed representative for the areas of intensive crop production in the Kujawy region.

SITE DESCRIPTION

Hydrological studies were carried out in the upper Zgłowiączka River watershed representative for the Kujawy region (sometimes referred to as Kuyavia or Cuyavia) [SMARZYŃSKA 2013]. The analysed watershed is closed by the river cross-section in Samszyce. Its area amounts to 78 km^2. Borders of the watershed were delineated using SWAT (soil and water assessment tool) based on digital elevation model with resolution of 90 m obtained from the Shuttle Topography Radar Mission. Detailed description of the SWAT model set-up for the analysed watershed was given by SMARZYŃSKA, MIATKOWSKI [2016].

Delineated watershed area is smaller by approximately 7 km^2 comparing with the area reported by BARTCZAK *et al*. [2014] determined on the basis of the digital Map of Hydrographic Division of Poland (1: 50 000) [IMGW-PIB 2007] made by the IMGW-PIB, ordered by the Ministry of Environment and financed by the National Fund for Environmental Protection and Water Management. The discrepancies refer to the northeastern part of the watershed. A precise delineation of sub-watersheds' borders in the Zgłowiączka River catchment is a complicated and difficult task due to changes in natural hydrological conditions resulting from installation of drainage system (consisting of tile drainage and open ditches) in the catchment [K-P ZMiUW 2010].

According to the regional division of Poland [KONDRACKI 2001], the research watershed is located within the two mezoregions: the Inowrocław Plain (315.55) and the Kujawy Lakeland (315.57). Northern part of the Kujawy Lakeland, within which lies the majority of the watershed, is a flat moraine (Fig. 1), with minimal height difference not exceeding 3 m, built mainly of glacial till [BARTCZAK 2007].

The Zgłowiączka River, 79 km in length, is a left-hand tributary of the Vistula River. The source of the Zgłowiączka River is located in the Płowce village, 92.5 m a.B.s.l. [BARTCZAK 2007]. In its upper part, from the source to the Głuszyńskie Lake (80.2 m a.B.s.l.), the Zgłowiączka River is a field-ditch. Its length to the river cross-section Samszyce amounts to 11.2 km (Tab. 1). The upper and middle part of the river (7.6 km long) is an intermittent stream, fed by water flowing from the drainage system in periods when soil water content exceeds field capacity.

In 2004 the upper part of the Zgłowiączka catchment (from source of the river to the Głuszyńskie Lake) was designated as a Nitrate Vulnerable Zone (NVZ). Currently the area of the NVZ Zgłowiączka amounts to 480 km^2 [Rozporządzenie... nr 5/2012] (32% of the Zgłowiączka catchment). Quality of sur-

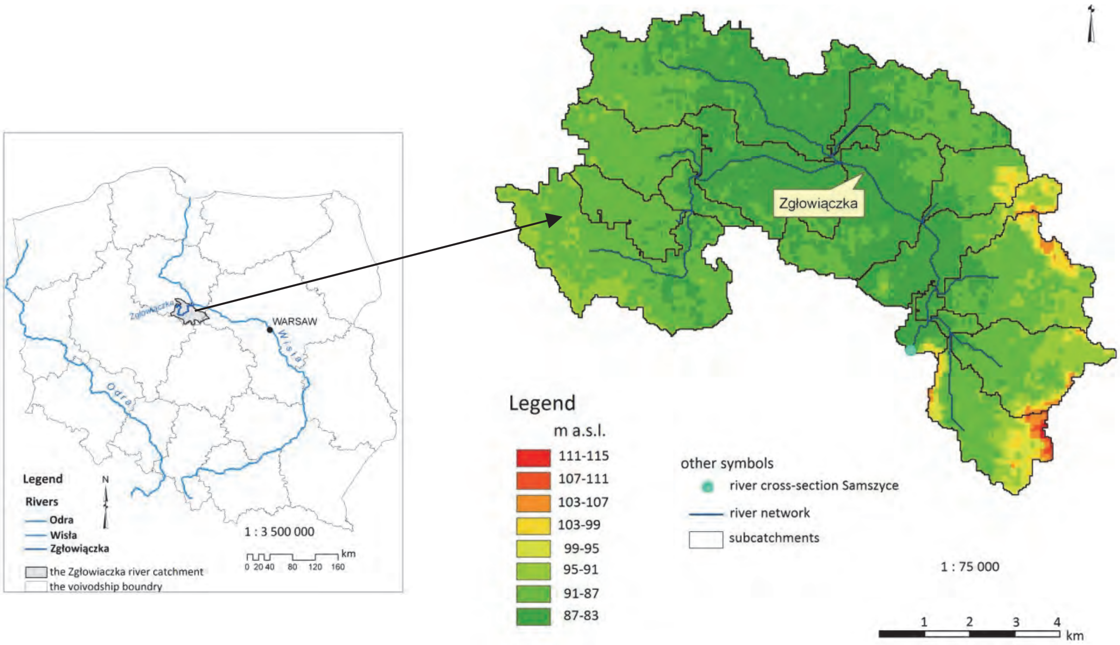

Fig. 1. Location of the study area and hipsometric map of the research watershed; source: own elaboration

Table 1. Physical and geographical parameters of the research watershed

Parameter	Value in river cross-section Samszyce
Watershed area, km^2	78
Length of main stream, km	11.2
Total length of streams, km	26.5
River network density, km·km^{-2}	0.3
Average catchment slope, ‰	3.6
Average slope of main stream, ‰	0.8
Percent of afforestation	4.0

Source: SMARZYŃSKA, MIATKOWSKI [2016].

face waters of the river is still poor and threatened by failure to achieve environmental objectives [Rozporządzenie... nr 27/2015].

The Kujawy region belongs to one of the driest in Poland, with the average annual precipitation amounting to 513 mm [ROGUSKI *et al.* 1996].

Dominant soil types are Phaeozems (about 85% of the watershed area). Field water capacity of these soils (for profile with depth of 150 cm) is high and varies between 160–200 mm, depending on the soil texture. Due to high quality of soils arable lands prevail in the watershed (90% of the area), whereas permanent grasslands occur only in small local depressions. The main cultivated crops are: cereals, maize, winter oilseed rape and sugar beet. According to "Atlas niedoborów wodnych…" [OSTROWSKI, ŁABĘDZKI (ed.) 2008] water deficits with probability of occurrence $p = 50\%$ (every second year) in the Kujawy region amounts to: 0–40 mm for winter oilseed rape, 40–80 mm for winter wheat and maize, 80–120 mm for sugar beet.

Because of periodic occurrence of water surpluses in soil profile and the need to create favourable conditions for crops cultivation, around 65% of the analysed area was drained. The drainage system is a combination of tile drainage and open ditches.

METHODS

Hydrometric measurements were carried out in the river cross-section Samszyce located at 67.8 km of the river length. Since 2006 water level has been constantly recorded in this point (with hourly time step). Water velocity in the river bed has been regularly measured (twice a month, in periods of high flows – once a week) since 2007 with the current meter Seba M1. The studies period included hydrological years 2007–2011. Hourly values of discharge were calculated on the basis of the flow rate curve equation determined for the river cross-section Samszyce.

Daily meteorological data: precipitation, minimum and maximum air temperature, relative air humidity and wind speed were obtained from the climatologic station in Kołuda Wielka (52°44' N, 18°08' E), and solar radiation from the Regional Hydro-Meteorological Station in Toruń (53°00' N, 18°36' E) and Hydro-Meteorological Station in Koło (52°11' N, 18°38' E). All the weather stations belong to the measuring system of the IMGW-PIB.

The disposable water resources were determined as a difference between gross water resources (understood as a mean discharge in multiyear – *SSQ*) and reserved flow (Q_{nn}) which in this study was calculated using two different approaches: by KOSTRZEWA [1977] and by SZYMCZAK [2013].

In the first method, commonly used for the practical purposes, Q_{nn} is calculated based on the average low discharge (*SNQ*) according to the equation (1):

$$Q_{nn} = SNQ \cdot k \quad (1)$$

where: SNQ = the average low discharge ($m^3 \cdot s^{-1}$); k = the empirical coefficient, which for lowland catchments and with area less than 1 000 km^2 is equal to 1.

This value is recommended also by the Regional Water Management Authority in Warsaw [Rozporządzenie... nr 5/2015] for the upper Zgłowiączka River, from the source to the Głuszyńskie Lake. However, in the case of small catchments this method may not be sufficiently precise and calculated reserved flow may be underestimated [SZYMCZAK 2002].

In SZYMCZAK [2013] approach assumption is made, that Q_{nn} for lowland catchments with an area below 500 km^2 should not be less than 60% of the SSQ due to smaller water resources of these catchments in low water periods linked with relatively smaller base flow.

Calculation of potential evapotranspiration (*PET*) was done using the SWAT model according to the Penman–Monteith formula [MONTEITH 1965; NEITSCH *et al.* 2005] with daily time step and alfalfa at a height of 40 cm as a reference crop. Climatic water balance of the research watershed was estimated as a difference between precipitation and *PET*. The remaining calculations were carried out using Statistica 7.1 (determination of the flow rate curve equation) and MS Excel 2007.

RESULTS AND DISCUSSION

PLUVIAL CONDITIONS AND HYDROLOGICAL REGIME

The upper Zgłowiączka River has a snow-rainfall hydrological regime, strongly modified by anthropogenic activities related to intensive crop production and installation of subsurface drainage system.

The study period was characterised by very large temporal variability of pluvial and hydrological conditions. Precipitation total in the first year (2007) of the study corresponded to precipitation sum for this region at the probability of non-exceedance (p) equal to 80% [ROGUSKI *et al.* 1996], which can be considered as very wet pluvial conditions. In the fourth year (2010) pluvial conditions were abnormally wet as annual sum of precipitation was close to the value at p = 90%. Remaining three years were average. Precipitation sums in the summer half-year (V–X) were always higher than in the winter half-year (XI–IV) (Tab. 2).

Several months of the studies period were characterised by extremely high precipitation, with sums close to these at p = 90% (likely to occur every 10 years, marked in bold in Tab. 2) and p = 99% (likely to occur every 100 years, bold and underlined).

Table 2. Precipitation totals in subsequent months and periods

Hydrological year	Month and period															
	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX	X	XI–IV	V–X	XI–X	I–XII
2007	37	32	**68**	**42**	**60**	13	37	65	**141**	69	32	13	252	357	609	571
2008	29	26	**65**	27	48	37	29	19	45	82	33	**69**	232	277	509	483
2009	13	16	16	22	38	4	65	**100**	**147**	32	22	46	109	412	521	568
2010	46	31	40	17	29	35	**97**	29	**119**	**124**	51	4	198	424	622	712
2011	**112**	54	29	22	17	6	32	71	110	34	34	13	240	294	534	403

Explanations: marked in bold = non-exceedance probability p = 90%; bold and underlined = non-exceedance probability p = 99%.
Source: data recorded at the Kołuda Wielka weather station – the IMGW-PIB.

In the analysed period 2007–2011 the average outflow coefficient amounted to 18% and unit outflow to 3.2 $dm^3 \cdot s^{-1} \cdot km^{-2}$ (Tab. 3). This value is slightly higher than the average for the entire Zgłowiączka catchment in multiyear 1951–2012 amounting to 2.51 $dm^3 \cdot s^{-1} \cdot km^{-2}$ [BARTCZAK *et al.* 2014].

Average outflow coefficient was similar to the values noted for the other catchments located in the lowlands of central Poland [BANASIK, HEJDUK 2012; LIBERACKI 2011; OSTROWSKI, ZANIEWSKA 2001] and for the Łutownia River catchment situated in the Białowieża Primeval Forest [PIERZGALSKI *et al.* 2006].

Table 3. Total/unit outflow and outflow coefficient of the research watershed

Hydrological year	Total outflow mln m^3	Unit outflow $dm^3 \cdot s^{-1} \cdot km^{-2}$	Outflow coefficient, %
2007	1.5	0.6	3
2008	1.2	0.5	3
2009	1.7	0.7	4
2010	9.5	3.8	20
2011	25.8	10.5	62
Mean	7.9	3.2	18

Source: own study.

Both variables varied highly in the subsequent years of the study. In 2007–2009 outflow coefficient was very low and amounted between 3 and 4% of annual precipitation, whereas in 2010 and 2011 – 20 and 62%, respectively (Tab. 3). In 2011 – the last year of the study the value of annual outflow coefficient was higher than the average for mountain catchments in Poland, which ranges from 41% [OSTROWSKI, BOGDAŁ 2006] to 56% [KANOWNIK, KOWALIK 2010]. Consequently, also average annual unit outflow from the research watershed varied from year to year. In the first three years its values were similar and ranged from 0.5 to 0.7 $dm^3 \cdot s^{-1} \cdot km^{-2}$, whereas in the fourth and fifth year were significantly higher amounting to 3.8 and 10.5 $dm^3 \cdot s^{-1} \cdot km^{-2}$, respectively (Tab. 3).

In 2007–2009 the mean unit outflow amounted to 0.6 $dm^3 \cdot s^{-1} \cdot km^{-2}$. This value is much lower than the mean unit outflow reported for the Kujawy region in the literature [GUTRY-KORYCKA *et al.* 2014; LESZ-

CZYCKI (ed.) 1994], but similar to the lowest values of the mean annual unit outflow for the eastern part of the Kujawy region (0.54 $dm^3 \cdot s^{-1} \cdot km^{-2}$) noted by BARTCZAK *et al*. [2014].

The average total outflow amounted to 7.9 mln m^3, varying from 1.2 mln m^3 in 2008 to 25.8 mln m^3 in the last year of the study. November was the month with the highest average outflow, while October – with the lowest (23 and 2% of the average annual outflow, respectively) (Fig. 2). The winter outflow (XI–IV) dominated. Its share in annual outflow was equal to 79%, indicating a large disproportion between the outflow sum in the winter and summer half-years (Fig. 2).

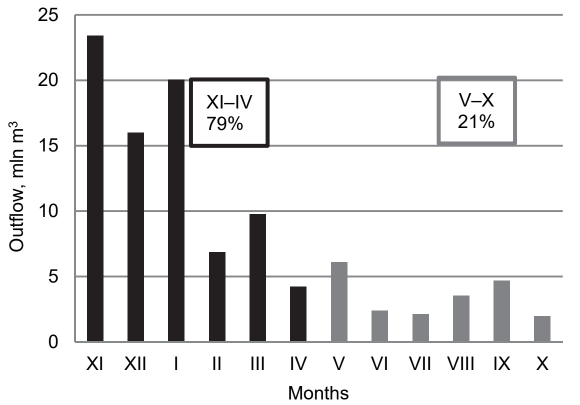

Fig. 2. Average monthly values of outflow in 2007–2011; source: own study

The average discharge (*SSQ*) of the upper Zgłowiączka River in the cross-section Samszyce in the years 2007–2011 amounted to 0.25 $m^3 \cdot s^{-1}$ (Tab. 4). This is almost double less than for the Mała Wełna River located also in the lowlands of central Poland [KANCLERZ *et al*. 2008].

The last year of the study (2011) was exceptional in terms of hydrological conditions. The highest values of daily discharge, exceeding 8 $m^3 \cdot s^{-1}$, were noted in this year and occurred during two water risings (Fig. 3). The first one, lasting 35 days, was a result of heavy rains and extremely wet conditions of November 2010 (see Tab. 2). The second one (lasting 29 days) occurred in January 2011 after rapid melting of snow cover resulting from rising of the air temperature. During the highest daily discharge in the year (equal to 8.39 $m^3 \cdot s^{-1}$), unit outflow from the watershed area amounted to 107.5 $dm^3 \cdot s^{-1} \cdot km^{-2}$. The minimum unit outflow in the same year amounted to 0.08 $dm^3 \cdot s^{-1} \cdot km^{-2}$. Around 85% of the total annual outflow was formed during the first three months of the analysed hydrological year (November, December, January).

Table 4. Characteristic discharge of the upper Zgłowiączka River

Hydrological year	Characteristic discharge, $m^3 \cdot s^{-1}$		
	WQ	*SQ*	*NQ*
2007	0.210	0.047	0.018
2008	0.199	0.038	0.016
2009	0.216	0.052	0.016
2010	1.967	0.296	0.033
2011	8.388	0.790	0.006
2007–2011	*SWQ*	*SSQ*	*SNQ*
	2.196	0.245	0.018

Source: own study.

In November the entire sum of precipitation (112 mm) was transformed into the outflow (Fig. 4) because rainfall in the previous months (especially in extremely wet August 2010) supplemented soils with water to total soil water capacity. The volume of outflowing water calculated using the flow rate curve was equal to the one estimated basing on the sum of precipitation for November 2011 and amounted to 8.7 mln m^3.

To illustrate the large variation of the hydrological process of rainfall to outflow transformation in the analysed watershed in different periods of the year, we compared November 2010 (autumn, hydrological year 2011) with July 2011 (summer). The monthly precipitation sums were almost the same (see Tab. 2). In the summer time the outflow deficit amounted to 0.7 mm (Fig. 5) what is equal to 0.6% of the monthly precipitation. The total monthly precipitation sum

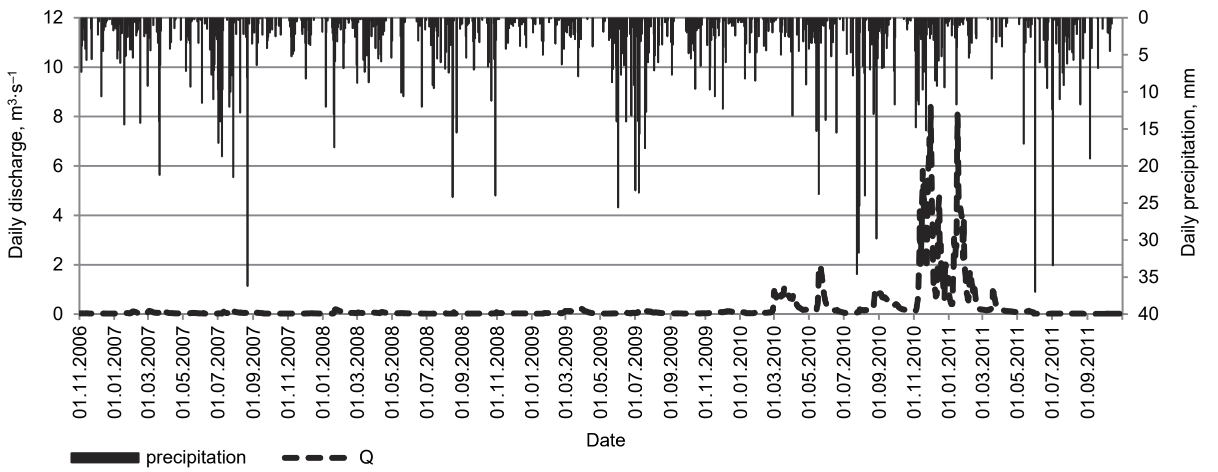

Fig. 3. Daily precipitation (mm) and discharge ($m^3 \cdot s^{-1}$) in the years 2007–2011; source: own study

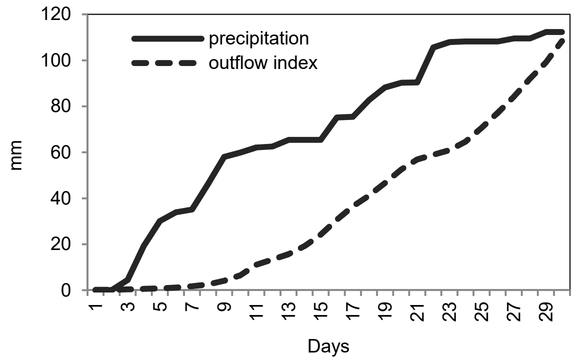

Fig. 4. Cumulative values of daily precipitation and outflow index in November 2010; source: own study

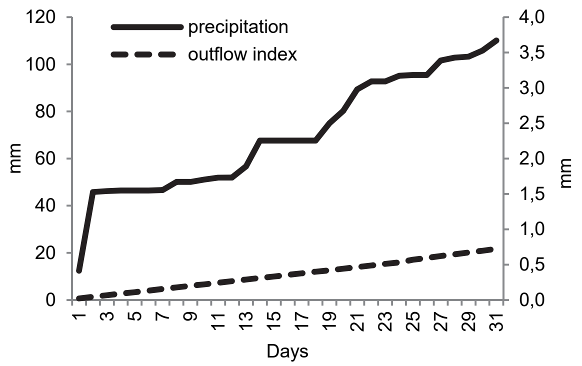

Fig. 5. Cumulative values of daily precipitation and outflow index in July 2011; source: own study

completed the soil water deficit resulting from the intensive crop growth.

From the beginning of April 2011 to the end of the hydrological year the daily discharge noted in the river cross-section Samszyce was below the *SSQ*, reaching the minimum in June. It was a result of dry conditions in May 2011 following extremely dry conditions in April.

The ratio of maximum to minimum average monthly outflow for the research watershed was equal to 12. This value is almost six times higher than for the country [MIODUSZEWSKI 2012]. The double-digit ratio is typical for mountain streams and small lowland water courses. The large temporal variability of precipitation and discharge causes water shortages (during growing season), but also floods in river valleys (like it happened in November 2010 and January 2011 in the upper Zgłowiączka River watershed).

SURFACE WATER RESOURCES AND WATER BALANCE OF THE KUJAWY REGION

The disposable water resources of the upper Zgłowiączka River watershed in the years 2007–2011 determined on the basis of the hydrobiological criterion [KOSTRZEWA 1977] amounted to 0.23 $m^3 \cdot s^{-1}$ and average disposable unit outflow (*Wqd*) – 2.91 $dm^3 \cdot s^{-1} \cdot km^{-2}$ (Tab. 5).

Table 5. Reserved flow (Q_{nn}), disposable unit outflow (*Wqd*), disposable flow and surface water resources (*Hd*) of the watershed

Parameter		Kostrzewa's approach	Szymczak's approach
Q_{nn}, $m^3 \cdot s^{-1}$		0.02	0.15
Wqd, $dm^3 \cdot s^{-1} \cdot km^{-2}$		2.91	1.26
Disposable flow, $m^3 \cdot s^{-1}$		0.23	0.09
Hd, mln m^3 (mm)	XI–X	7.0 (90)	3.0 (40)
	XI–IV	5.8 (75)	2.5 (32)
	V–X	1.2 (15)	0.5 (8)

Source: own study.

The reserved flow index (*Wqnn*) for the upper Zgłowiączka River watershed, estimated using SZYMCZAK approach [2013], amounts to 1.88 $dm^3 \cdot s^{-1} \cdot km^{-2}$. The difference between *Ssq* (mean unit outflow) and *Wqnn* determines *Wqd*, which is equal to 1.26 $dm^3 \cdot s^{-1} \cdot km^{-2}$. This value is more than twice lower comparing with the one calculated using Kostrzewa's equation, but similar to values for other small catchments located in Central Polish Lowlands belt [SZYMCZAK 2013]. The difference between amount of surface water resources estimated using two different methods results of various approach to determination of reserved flow.

According to our results the study area is characterised by the low and varying in time disposable resources of surface water with simultaneously high water needs of intensive crop production. The small surface water resources practically exclude the possibility of water uptake for irrigation during the growing season. Thus, the use of the water resources for agricultural purposes is impossible without increase in water retention. This issue concerns not only the analysed watershed or the Kujawy region in general, but also the other lowland catchments in central Poland [SZYMCZAK 2013].

Analysing the results of water balance for individual years the large temporal variability of its components is noticeable (Tab. 6).

Table 6. Water balance (mm) of the watershed in 2007–2011

Hydrological year	Precipitation	Outflow index	Outflow deficit
2007	607	19	588
2008	509	16	493
2009	520	22	498
2010	622	121	501
2011	534	330	204
Mean	558	102	456

Source: own study.

In 2011 the outflow index was much higher than the outflow deficit. Almost 22 mln m^3 of water flowed out during the first three months of this year. It is more than the summed outflow from all previous years of the study (see Tab. 3). Such a large outflow indicates a low retention capacity of the watershed in conditions when the soil water content is equal to the field water capacity. Moreover, the tile drainage accelerates water cycle within the watershed. The old type of drainage system installed in the research area gives a very limited opportunity to control the amount of water entering drainage pipes. Land use structure is unfavourable for water retention – only 4% of forest areas. Forest has a positive impact on water cycle of the catchment by aligning the outflow [STASIK *et al*. 2007]. Furthermore, the upper part of analysed river is an intermittent watercourse with no base flow, what is nothing unusual in the case of small watersheds located in the lowlands of central Poland [SZYMCZAK 1997].

CLIMATIC WATER BALANCE

The climatic water balance (*CWB*) indicates the risk of agro-climatic drought. It can be used to evaluate crop water demands, agricultural droughts and irrigation requirements [KASPERSKA-WOŁOWICZ, ŁABĘDZKI 2006].

In the time of intensive crops growth and the highest water needs (April–June) *PET* significantly exceeded monthly precipitation totals in the research watershed. Hence, values of the *CWB* were negative (Fig. 6). The greatest deficit of precipitation in relation to *PET* occurred in June and amounted to 59 mm. Recent studies suggest that decrease of the *CWB* in spring and early summer is typical for the whole country [DOROSZEWSKI *et al*. 2012].

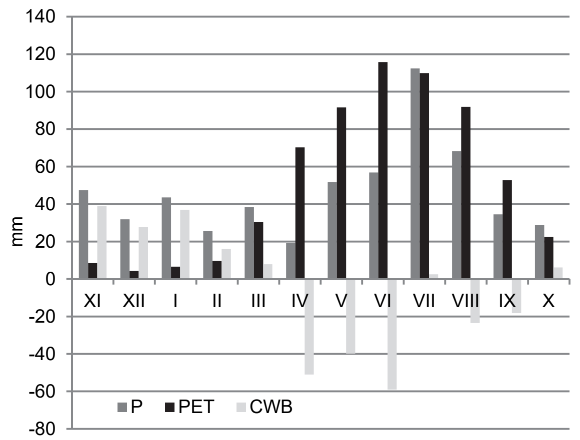

Fig. 6. Mean precipitation sum (*P*), potential evapotranspiration (*PET*) and climatic water balance (*CWB*) in subsequent months; source: own study

Long-lasting dry periods (subsequent days without rainfall) are a characteristic feature of the Kujawy region climate. They occur not only in dry years but also in average and wet. According to KASPERSKA-WOŁOWICZ *et al*. [2003], about 50–60 days with atmospheric drought may be expected every year in the region and dry periods may occur every month. They are considered to be the atmospheric phenomena causing the greatest yield lost in agriculture.

As dry periods are very likely to occur every year in the analysed region, drought and water scarcity are the most significant issues for farmers in the Kujawy region related to climate and its projected change. Forecasted climate change for the Kujawy region will result in decrease in the amount of rainfall during the growing season by approximately 55 mm, compared to 1971–2000 taken as a reference period, and increase of agricultural droughts intensity [BĄK, ŁABĘDZKI 2014], which is related to increase of water needs for irrigation. Results of recent studies suggest that there is a consistent correlation between farmers' past climate experiences, local level concerns or limiting factors for future, and the adoption of agricultural adaptation practices [NILES *et al*. 2015]. Farmers' adaptive behaviour to climate change within an agricultural system is influenced by the most limiting factor. Agricultural drought seems to be the "fundamentally" close phenomenon to farmers and water is expected to be the key limiting factor for the agriculture sector in the future. Farmers' adoption strategies in the Kujawy region consist in development of individual sprinkler irrigations based on deep groundwater resources [Starostwo… 2008]. This solution, i.e. use of clean, long-renewable groundwater resources seems to be a questionable and only temporary method of preventing water shortages in crop production. Collection of water surpluses (during spring thaw or after heavy rainfall in summer) in reservoirs or ponds for irrigation purposes is the most effective way to use low and varying in time surface water resources of the analysed region. Irrigation ponds, a small-size type of water-supply structure, are very popular in many agricultural regions affected by water shortages [LI *et al*. 2016; MIODUSZEWSKI 2004]. Additionally, tile drainage is the main path of nitrates movement within the analysing watershed. Its share in total NO_3-N load was equal to 89% [SMARZYŃSKA, MIATKOWSKI 2016]. Thus, the collection and management of drainage waters should be considered by the local authorities as a method of nitrogen load reduction and surface water quality protection.

CONCLUSIONS

The paper presents results of the 5-year hydrologic studies (2007–2011) carried out in the agricultural watershed situated in the Kujawy region. This region belongs to one of the driest in Poland but at the same time – with high water needs related to intensive agricultural production. The paper contains also an analysis of the *CWB* as an indicator of crop water demands and surface water resources – as a potential source of water for crop irrigation in the region.

In the analysed period the mean annual outflow coefficient amounted to 18%, varied highly in time from 3% in the average years to 62% in the abnormally wet 2011. November was the month with the highest average outflow, while October – with the lowest. The outflow dominated in the winter half-year and its share in annual outflow was equal to 79%. Average discharge (*SSQ*) in the Samszyce river cross-section was equal to 0.254 $m^3 \cdot s^{-1}$, and the mean unit outflow – to 3.2 $dm^3 \cdot s^{-1} \cdot km^{-2}$. According to our results, the soil retention is the only form of water retention in the watershed. When the soil moisture exceeds field water capacity, in wet pluvial conditions the total monthly precipitation sum can be transformed into an outflow.

Average values of the *CWB* calculated for the research watershed were negative in all subsequent months of the growing season (IV–IX), except in July. The greatest deficit of precipitation in relation to potential evapotranspiration occurred in June. The *CWB* for the average summer half-year (V–X) amounted to –132 mm.

The results of our study show that disposable surface water resources of the Kujawy region are very small, especially in the summer half-year. In this period they ranged from 0.5 mln m^3 (8 mm) to 1.2 mln m^3 (15 mm), depending on the applied calculation method. Comparison of these values with the corresponding value of the *CWB* points out that there is not enough water in the river and its tributaries to meet potential crop water demands. The mismatch between water resources supply and demand of irrigation can become a serious problem, if the climate change forecasts for the Kujawy region will come true. Very limited surface water resources and their large seasonal and long-term variability prevent the planning of any economic activities with the use of these resources. At the same time, water excesses occurring randomly (mainly in the non-growing season) and accompanying large nitrogen load indicate an urgent need for water retention within the watershed for irrigation purposes. In these conditions integrated management of surface and ground water for irrigation may pose an opportunity for optimal use of surface water resources and reduction of nitrogen load.

The data and analyses of hydrological regime of the upper Zgłowiączka River and surface water resources of the Kujawy region could provide the useful information for local water management authorities to develop adaptation strategies of agricultural sector to climate change. According to results of the recent studies, regional and local-based adaptation strategies will likely be the most effective to deal with the problems of global warming and water shortages in agriculture sector.

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Zasoby wodne małej zlewni rolniczej w regionie Kujaw, centralna Polska

STRESZCZENIE

Celem artykułu jest określenie wielkości zasobów wód powierzchniowych zlewni rzecznej reprezentatywnej dla obszarów intensywnie użytkowanych rolniczo w regionie Kujaw. Teren ten charakteryzuje się najniższą średnią roczną sumą opadów w Polsce oraz dużymi potrzebami wodnymi wynikającymi z intensywnej produkcji rolniczej.

Badania hydrologiczne były prowadzone w latach 2007–2011 w zlewni górnej Zgłowiączki zlokalizowanej we wschodniej części analizowanego regionu. Ponad 90% obszaru badań jest użytkowane jako grunty orne. Prędkość przepływu wody w korycie cieku oraz poziom wody były mierzone w przekroju hydrometrycznym zamykającym zlewnię w Samszycach.

Górna Zgłowiączka charakteryzuje się śnieżno-deszczowym reżimem hydrologicznym, silnie przekształconym antropogenicznie (intensywna produkcja roślinna oraz instalacja systemu drenarskiego). W okresie badań odnotowano dużą zmienność czasową warunków hydrologicznych. Średni roczny współczynnik odpływu wyniósł 18%, zmieniając się znacznie w czasie – od 3 w latach przeciętnych do 62% w anormalnie mokrym 2011 r. Średni odpływ (*SSQ*) w przekroju hydrometrycznym w Samszycach wyniósł 0,25 $m^3 \cdot s^{-1}$, a średni odpływ jednostkowy – 3,2 $dm^3 \cdot s^{-1} \cdot km^{-2}$. Wyniki badań wskazują, że zasoby wodne Kujaw są bardzo małe, szczególnie w półroczu letnim. W związku z tym wykorzystanie tych zasobów jako potencjalnego źródła wody do nawodnień może być rozważane pod warunkiem retencjonowania nadmiarów wody na obszarze zlewni i ich eksploatacji równocześnie z zasobami wód gruntowych.

Słowa kluczowe: *klimatyczny bilans wodny, region Kujaw, reżim hydrologiczny, współczynnik odpływu*