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Annual and seasonal precipitation patterns across lowland catchment derived from rain gauge and weather radar data

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Abstract

Weather radar technology offers a unique means for hydrological applications characterizing precipitation patterns with high space-time resolutions. In this paper rain gauge and weather radar data are applied simultaneously to improve the knowledge of seasonal and annual amount of precipitation in a protected wetland catchment in central Poland. Analysis of precipitation patterns in years 2004–2008 has demonstrated that significant improvement in the accuracy of precipitation estimation at a catchment scale can be achieved when applying radar data. Two slightly different zones have been detected within the catchment, regarding its annual and seasonal precipitation characteristics. Analysis has proved that the west part of the catchment is recharged by relatively lower precipitation in comparison to the east part situated in the vicinity of Warsaw agglomeration. Spatial differences in precipitation recharging subsurface water resources have revealed the reduced precipitation in wetland areas which are of special environmental importance. Recommendation refers to the use of high resolution rainfall data responding to the demand for better hydrological process understanding. Described technique, apart from purely hydrologic applications, may be used to identify the subsurface recharge in the areas of high environmental concern for solving water management problems.

Key words: *rain gauge precipitation, spatial and temporal patterns, weather radar precipitation*

INTRODUCTION

Estimation of the spatial and temporal distribution of precipitation is an essential issue in hydrological applications. The demand for better understanding of hydrological processes at different spatial scales requires application of more integrated and advanced techniques of rainfall detection and estimation rather than applying data from conventional networks of ground based rain gauges only. Responding to this growing demand, the quantitative precipitation estimates derived from weather radar technology can be used both in operational hydrology as well as in particular case studies. This source of data offers a unique opportunity to describe the heterogeneity of rainfall fields, especially in terms of spatial distribution [PARZYBOK *et al.* 2010]. Thus these data can support the water balance studies [DUGAS, ARKIN 1984; HE *et al*. 2011], distributed hydrological modeling in gauged and un-gauged catchments [CARPENTER, GEORGAKAKOS 2001; COLE, MOORE 2009] as well as hydrological prediction [LOBBRECHT *et al.* 2011]. Therefore such derived quantitative precipitation estimates can substantially contribute to hydrological characterization of catchments, especially in locations where ground collection of rainfall data is limited by resources, feasibility and infrastructure [WEISSLING, XIE 2009].

The objective of this study is to evaluate and demonstrate how weather radar data corresponding to relevant ground rain gauges data may be used to improve the accuracy of precipitation estimates across a catchment. The primary implication of this research is the evaluation of precipitation characteristics at annual and seasonal time scales to facilitate the water balance studies and water resource management. The study area is the Łasica catchment located in central Poland within boundaries of the Kampinos National Park (N 52°15’–N 52°24’ and E 20°15’–E 20°57’). Valuable protected ecosystems, including wetlands, are present in the catchment [KOTOWSKI *et al*. 2009; MICHALSKA-HEJDUK 2004]. They are closely associated with recharge by rainfall and zones of shallow groundwater. Over the year spatial precipitation patterns and groundwater level influence seasonally the cycle of wetlands filling and drying. Over several years there may be places that are wetter or drier than average having an impact in longer-term on the level of wetness conditions. Thus the major objective of this study was to examine precipitation characteristics as a factor for ecosystems functioning and its maintenance.

DATA AND METHODS OF DATA PROCESSING

Precipitation data from rain gauges and from weather radar data were applied in this study selecting the period from the year 2004 to 2008. Areal estimates of rain gauge precipitation sums were calculated based on kriging method. Data were available from six rain gauge stations belonging to the network of the Institute of Meteorology and Water Management in Warsaw and from nine stations belonging to the network of the Kampinos National Park (Fig. 1). As the rain gauge measurements are only estimates at a point, radar precipitation data at high spatial resolution were acquired as a product derived from the weather radar situated in Legionowo, north to the analyzed catchment (latitude: 52°24'01", longitude: 20°55'53"). This weather radar belongs to the Polish radar network POLRAD that covers the whole territory of Poland. It is operated by the Institute of Meteorology and Water Management [SZTURC, DZIEWIT 2005]. The temporal resolution of the data was 10 min, the spatial resolution was 1 km and they were quality controlled [SZTURC *et al*. 2010]. Based on that, 3h-interval data were aquired for this study. Then monthly radar estimates in years 2004–2008 integrated from 3h-interval data were applied to analyze spatial patterns of precipitation.

Procedures of radar data processing comprise temporal data aggregation, comparison of radar precipitation with precipitation from rain gauges and generating radar maps at a catchment scale (Fig. 2). Radar data were aggregated within spatial domain from 3-hour interval into daily values accumulated from 06:00 to 06:00 UTC in summer and 07:00 to 07:00 UTC in winter. The extraction of daily radar precipitation at pixels including rain gauges was conducted using a built-in functions of Model Builder in ArcGIS Desktop version 10 to string sequences of geoprocessing tools together. To automate the procedure, first, a simple model developed as a toolbox was designed to extract the tables with value attributes by the ‘Zonal Statistics as Table’ tool (Fig. 3). The next

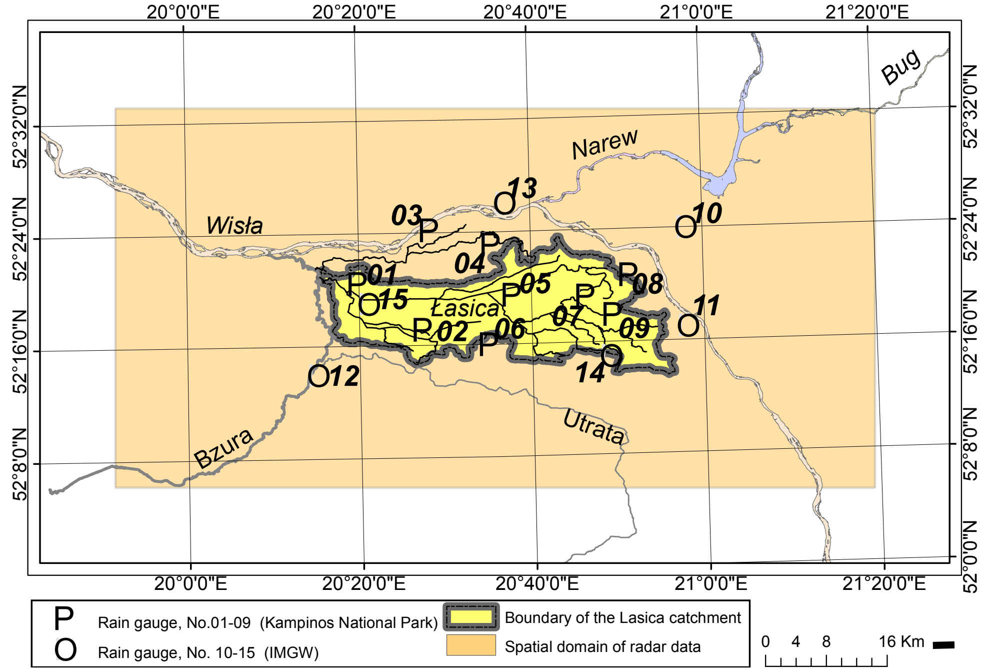

Fig. 1. Study area and rain gauge locations belonging to the networks of the Kampinos National Park and the Institute of Meteorology and Water Management (IMGW)

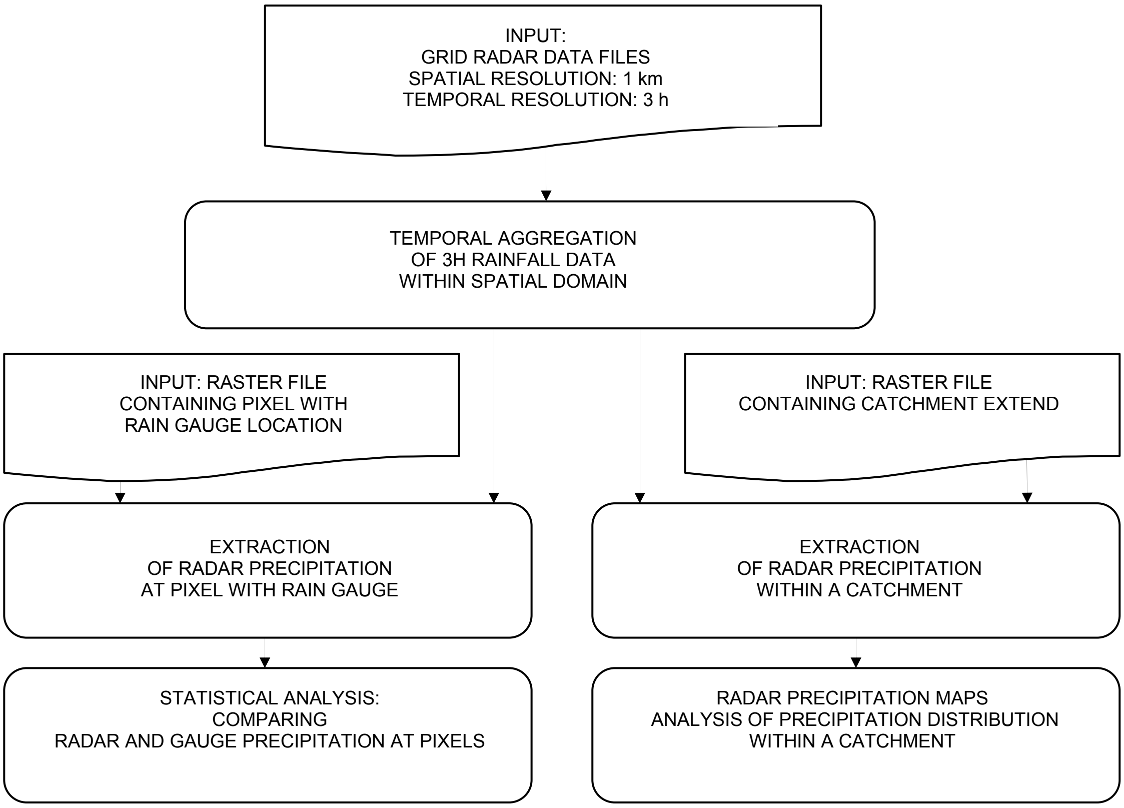

Fig. 2. The flowchart showing the sequence of radar data processing and analysis

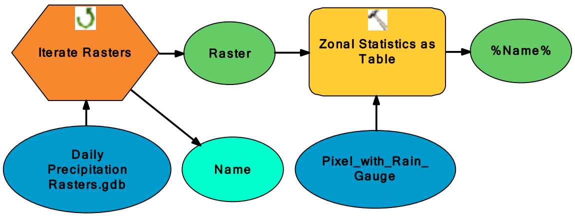

Fig. 3. Model toolbox in ArcGIS 10 – procedure of tables extraction with daily values of radar precipitation at pixel including a rain gauge

step of the procedure was to append daily pixel values stored in separate tables into a one table using the 'Append' tool (Fig. 4). The daily precipitation estimates from the weather radar were then evaluated through the comparison with precipitation measured by rain gauges at a scatter plot and by regression analysis. Furthermore, the extraction of the radar precipitation at a catchment scale was conducted generating radar maps and computing statistical measures of spatial distribution of precipitation.

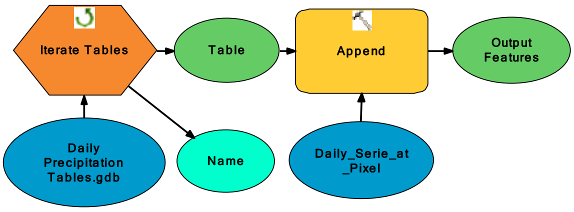

Fig. 4. Model toolbox in ArcGIS 10 – procedure of tables appending to derive daily series of radar precipitation at pixel including a rain gauge

COMPLIANCE OF THE RADAR ESTIMATES WITH THE RAIN GAUGE DATA

It is well known that neither radar estimates nor rain gauge data are free from errors [EINFALT *et al.* 2010]. Besides, rain gauge and radar are different precipitation measuring systems. Rain gauge makes a point measurements integrated over time at a ground, while radar samples precipitation by a volume above the ground. Nonetheless the two observation systems, weather radar and ground rain gauges, are generally treated as complementary systems and assumed to evaluate independently the same unknown quantity [ABDELLA, ALFREDSEN 2010]. Adjustment of radar data against rain gauge data allows to keep quantitative accuracy and at the same time spatial distribution detected by radar. For this study radar data were filtered to remove anomalous radar echo (speckle noise and permanent echo) and then adjusted using gauge-to-radar technique. The added value expected from using gauge adjusted radar product was to estimate the precipitation field over the entire catchment observed by the radar which intuitively is more precise than image interpolated from data acquired from a coarse network of rain gauges.

There are numbers of different efficiency criteria applied in hydrological studies to assess the "closeness" of the simulated behaviour of hydrologic variable to observations. Three most common efficiency criteria comprise coefficient of determination, Nash-Sutcliffe efficiency index and index of agreement [KRAUSE *et al.* 2005]. Here the coefficient of determination r^2 is applied and calculated as:

$$r^2 = \left(\frac{\sum_{i=1}^{n}(PG_i - \overline{PG})(PR_i - \overline{PR})}{\sqrt{\sum_{i=1}^{n}(PG_i - \overline{PG})^2}\sqrt{\sum_{i=1}^{n}(PR_i - \overline{PR})^2}} \right)^2$$

where:

PG_i – rain gauge precipitation for the time step i;
PR_i – radar precipitation for the time step i;
$\overline{PG}$ – mean rain gauge precipitation;
$\overline{PR}$ – mean radar precipitation.

In this study radar precipitation estimates have been evaluated through comparison of radar pixel values with measurements from rain gauges. Analysis was conducted for the time intervals of 1-day, 3-day and 7-day sums (Tab. 1). Data from rain gauge at Granica (No. 02) was excluded from the analysis due to erroneous values. Such finding was also proved by GOTTSCHALK *et al.* (2011). The value of r^2 is generally higher for longer time intervals and much smaller for the 1-day step. Possible explanation is the inaccuracy in rain-gauge data. In some cases a particularly high amount of precipitation is observed in the 1-day data collected within the rain gauge network belonging to the Kampinos National Park. It arises from incorrect entry of precipitation that occurred during couple of days and is wrongly registered by observers as a 1-day sum. At a longer time steps, e.g. at the 7-day step, such registration inaccuracies are automatically eliminated. Summarizing, the analysis has revealed that the mean amount of variance explained for the 3-day and 7-day time steps was within the range 73–78%, so most of the variance was explained by the linear regression model (Tab. 1). An example of the compliance between radar and rain gauge data is additionally shown at a Figure 5 using the cumulative precipitation curves. Although some discrepancies are observed, it is assumed that the radar data represent enough accurately the amount of point rainfall reaching the ground. Assuming relatively high compliance of two types of data, further analysis on spatial distribution of precipitation was conducted.

Table 1. The evaluation of the radar precipitation compliance with rain gauge precipitation for the year 2004: coefficient of determination r^2 calculated for 1-day, 3-day and 7-day precipitation sums; rain gauge at Granica (No.02) was withdrawn from the analysis due to erroneous values

Rain gauge	Coefficient of determination r^2		
	7-day sum	3-day sum	1-day sum
Rain gauge 01 Miszory	0.80	0.74	0.50
Rain gauge 02 Granica	0.00	0.00	0.01
Rain gauge 03 Wilków	0.76	0.70	0.52
Rain gauge 04 Rybitew	0.78	0.73	0.57
Rain gauge 05 Kiscienne	0.85	0.81	0.66
Rain gauge 06 Leszno	0.83	0.76	0.56
Rain gauge 07 Pociecha	0.72	0.64	0.45
Rain gauge 08 Dziekanów	0.71	0.66	0.47
Rain gauge 09 Izabelin	0.80	0.76	0.62
Mean r^2, excluding rain gauge 02	0.78	0.73	0.54

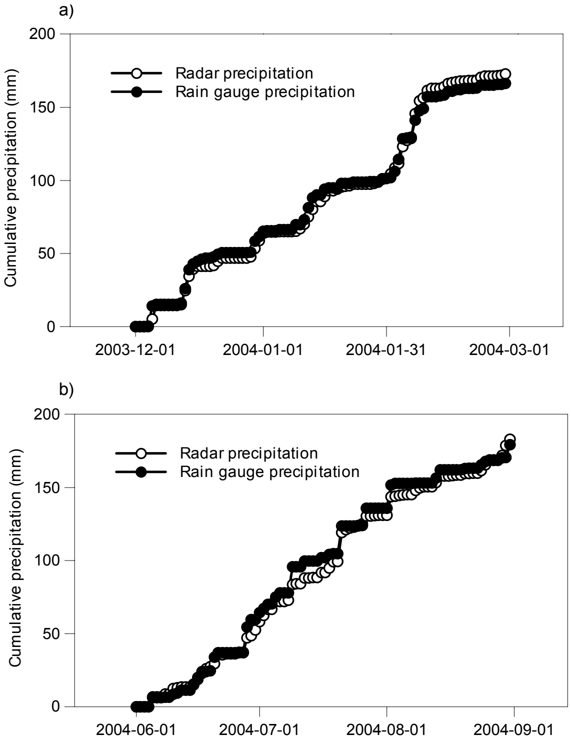

Fig. 5. Comparison of cumulative precipitation derived from daily rain gauge at Kiscienne (No. 05) and radar data for the 3-month period of the year 2004: (a) winter months: December–January–February, (b) summer months: June–July–August

DIFFERENCES BETWEEN RADAR AND GAUGE DERIVED SPATIAL PRECIPITATION ESTIMATES

Comparison between radar and gauge derived spatial precipitation patterns was conducted on the example of summer season precipitation for months from May through October. Mean summer precipitation map in years 2004–2008 was derived based on the rain gauge data using kriging method. Its resolution was adjusted to the resolution of radar precipitation map in order to compare precipitation values at a pixel scale. The number of pixels at the radar map as well as at the gauge derived map was equal to 465 and such number of value pairs were correlated.

Mean summer precipitation sum in years 2004–2008 derived from gauge data was equal to 296mm which was very close to the 292mm as a mean derived from radar data. Maximum differences in particular years reached the value of ±40mm. However the amount of variance explained between two sets of variables was only 52% caused by relatively high discrepancies observed at a pixel scale (Fig. 6). The most probable reason explaining this is too coarse resolution of rain gauges density. This fact causes the generalization of the gauge derived spatial precipitation patterns not sufficiently recognized by the network of rainfall stations. In this case precipitation field identified using kriging method only partially explains the spatial structure of precipitation recorded by radar.

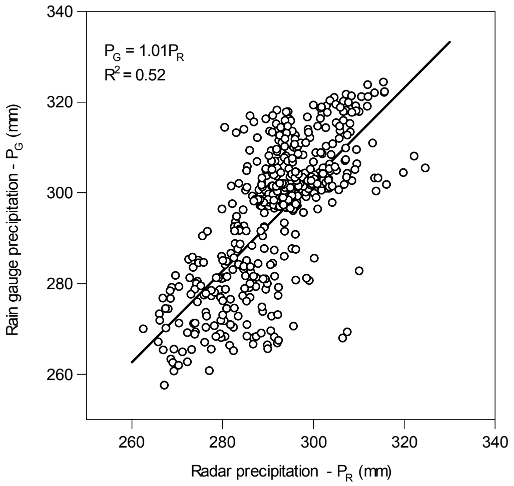

Fig. 6. Scatter plot of radar and rain gauge precipitation within boundary of the Łasica catchment. Plot consists of 465 pairs of values derived as mean summer precipitation sums in months from May through October; P_R – radar precipitation, P_G – rain gauge precipitation

RADAR PRECIPITATION PATTERNS ACROSS THE CATCHMENT

Precipitation varies substantially across the analyzed area (Fig. 7). The mean annual sum of precipitation recharging the spatial domain is 595 mm whereas in the Łasica catchment it equals to 583 mm. The catchment experiences a mixed winter-summer precipitation regime. Roughly 50% of that comes during the summer half of the year between May and October, with around 40% of the annual precipitation received between May and August (Fig. 8a). During these months, rainfall is received from summer storms causing a relatively high range of monthly precipitation amount at different places across the catchment (Fig. 8b). Such a high range of precipitation amount is

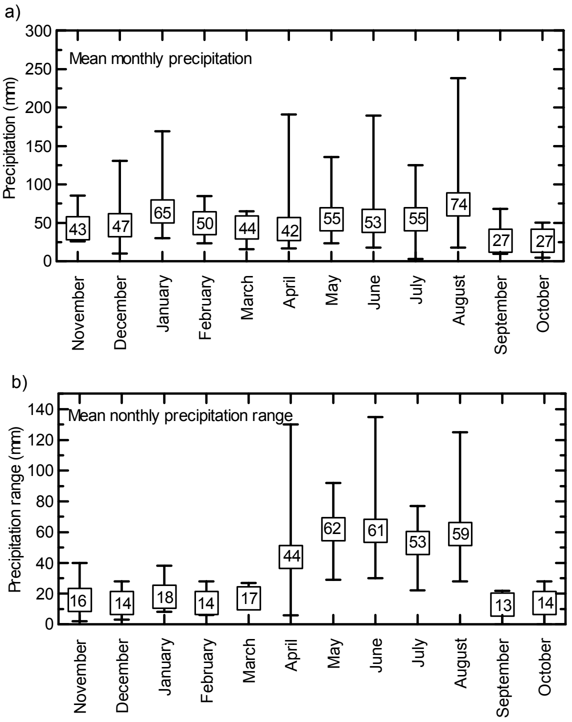

Fig. 7. Mean monthly precipitation sums (a) and mean monthly precipitation range (b); whiskers show extreme pixel values in particular months in years 2004–2008 registered in the Łasica catchment

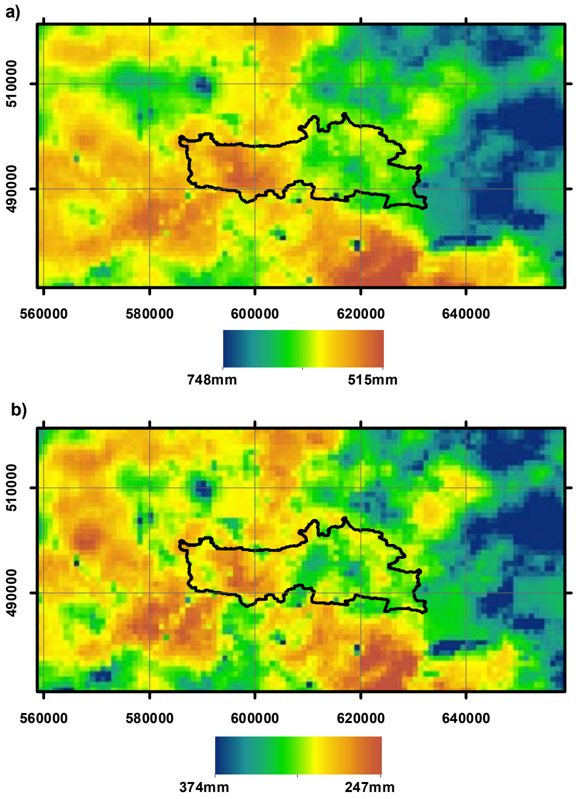

Fig. 8. Precipitation patterns within the Łasica catchment and its broad surroundings: mean annual values (a) and mean summer values in months May–October (b); maps derived as a mean values for years 2004–2008

observed in April as well. Much lower range appears during winter half of the year when the rainfall is received from a wide-spread precipitation of lower intensity. During the yearly course, the maximum monthly sums appear in August and minimum – in September and October.

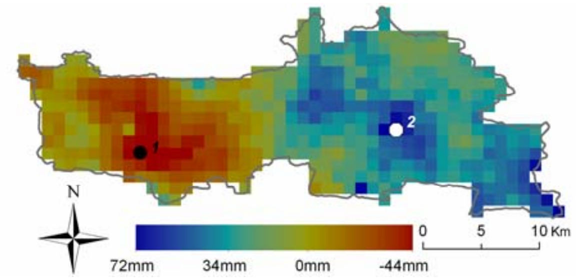

Fig. 10. Spatial anomaly in mean summer precipitation pattern within the Łasica catchment; symbols: *1* – pixel in the area of ecologically valuable ecosystems with lowest precipitation sums, *2* – pixel in the east part of the catchment recharged by relatively high precipitation

Table 2. Comparison of annual and summer precipitation characteristics calculated for the east and west part of the catchment and for the selected pixels

Period	Precipitation sums, mm Catchment			Precipitation sums, mm Extreme values in pixels		
	P_E	P_W	$P_E - P_W$	P_2	P_1	$P_2 - P_1$
Year 2006						
November–October	657	609	49	711	575	136
May–October	317	297	21	360	272	88
Year 2007						
November–October	729	683	45	810	644	167
May–October	342	314	28	426	273	153
Mean in years 2004–2008						
November–October	597	564	33	626	539	87
May–October	298	282	16	325	262	62

Explanations: P_E – precipitation sum in the east part of the catchment, P_W – precipitation sum in the west part of the catchment, P_1 – precipitation sum at pixel '1' (shown at the figure 10), P_2 – precipitation sum at pixel '2' (shown at the Figure 10).

Anomaly values calculated as a difference between pixel value and a mean for the whole spatial domain, have emerged the areas of the potential precipitation surplus and deficits (Fig. 9). The highest positive anomalies (precipitation sums above the areal mean) are detected in the east, partially covering the east part of the catchment. This can be explained by the presence of the Warsaw urban heat island and dominant western winds encountering a city as a barrier to surface airflow [LORENC 1991]. The highest negative anomalies (precipitation sums below the areal mean) were detected in the west and south part of the spatial domain. Anomaly values calculated within the catchment clearly show that precipitation deficits occur throughout the western part of the catchment (Fig. 10). Chosen precipitation characteristics estimated for the whole catchment as well as for the selected places with extreme precipitation values have been presented in Table 2. Differences in annual sums between east and west part of the catchment equals on average 33 mm and in particular years approach the value of 50 mm. However maximum differences between particular places (e.g. between site '1' and site '2' indicated at the Figure 10) are much higher. For example in the year 2007 the differences reached the values of 167 mm for the whole year and 153 mm for summer months respectively. Thus dominant amount of the precipitation difference in this particular year has appeared in summer.

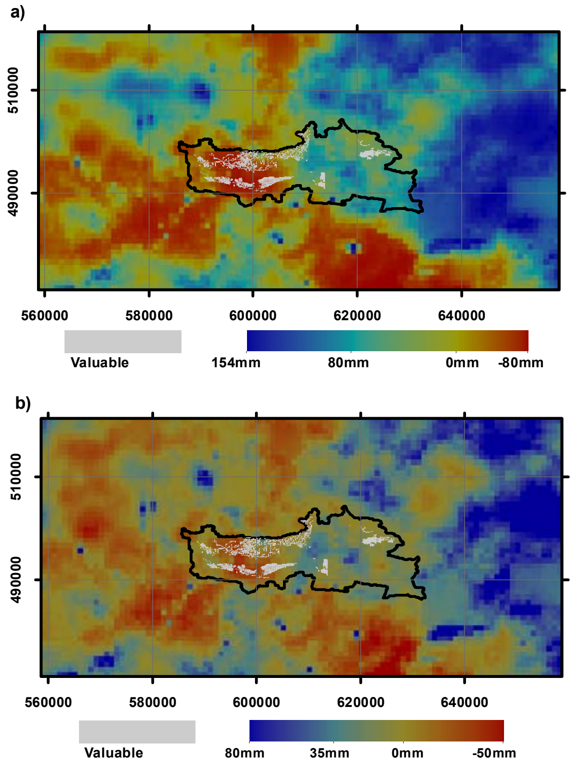

Fig. 9. Anomalies in annual precipitation patterns (a) and summer precipitation patterns (b) within the Łasica catchment and its broad surroundings. Grey color shows the location of the ecologically valuable ecosystems; maps derived as a mean values for years 2004–2008

Zone of the lower amount of the catchment precipitation surrounds the location indicated as point '1' at the Figure 10. It coincides with the presence of naturally valuable habitats classified as water-dependent ecosystems [DOMAŃSKA *et al.* 2010]. Thus this area can be considered as a precipitation deficit risk zone having an impact on the maintenance and renaturization of the ecologically important vegetation. The long term deficit in rainfall might create a barrier for its functioning [OKRUSZKO *et al.* 2011]. A prolonged drying out process, stimulated by lower precipitation, might affect reduced recharge of the soil water and in consequence – groundwater depletion.

CONCLUSIONS

Analysis has shown that the radar precipitation data significantly improved the spatial precipitation images analyzed at a seasonal and annual time scale. In this case the diverse nature of the spatial patterns was not sufficiently recognized by the network of rainfall rain gauge stations. Non-uniform catchment recharge was detected by radar precipitation images. It was demonstrated that the west part of the catchment is recharged by relatively lower precipitation in comparison to the east part situated in the vicinity of Warsaw agglomeration. Reduced precipitation in wetland areas has been proven.

Presented analysis of the spatial radar images can be considered as a basis for the estimation of precipitation as an element of water balance studies in the catchment of ecological importance. It may be applied in other environmental studies to detect the precipitation deficit risk zones or just inhomogeneities of precipitation recharge.

ACKNOWLEDGEMENT

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Urszula SOMOROWSKA

Roczna i sezonowa struktura pola opadu w zlewni nizinnej na podstawie danych naziemnych i radarowych

STRESZCZENIE

Słowa kluczowe: *czasowa i przestrzenna struktura pola opadu, dane naziemne, dane radarowe*

Radarowe techniki obserwacji pola opadu stanowią unikatowy element zastosowań hydrologicznych, charakteryzując opady z wysoką rozdzielczością przestrzenno-czasową. W niniejszym artykule przedstawiono wyniki rozpoznania sezonowej i rocznej zmienności opadu w chronionej zlewni bagiennej Łasicy, położonej w środkowej Polsce. Wykorzystano zarówno dane radarowe, jak i naziemne, pochodzące z posterunków opadowych. Analiza dotyczyła lat hydrologicznych 2004–2008. Wykazano, że stosowanie danych radarowych znacznie uszczegóławia pole opadu analizowane w skali zlewni. W zlewni wyróżniono dwie strefy, odmienne pod względem rocznych i sezonowych charakterystyk opadu. Wykazano, że zachodnia część zlewni jest zasilana przez relatywnie niższe opady w porównaniu z częścią wschodnią położoną w sąsiedztwie aglomeracji warszawskiej. Stwierdzono występowanie najniższych opadów na obszarach bagiennych, uznanych za szczególnie cenne przyrodniczo. Stosowanie danych radarowych o wysokiej rozdzielczości przestrzennej odpowiada potrzebie szczegółowej identyfikacji procesów hydrologicznych w skali zlewni. Niska rozdzielczość przestrzenna danych naziemnych może prowadzić do błędnych oszacowań, a w rezultacie powodować niedokładności identyfikacji opadu jako elementu bilansu wodnego. Opisana metoda oceny pola opadu, oprócz zastosowań wyłącznie hydrologicznych, może być stosowana do identyfikacji obszarów o podwyższonym ryzyku występowania deficytów wody, co jest przydatne w gospodarowaniu wodą, szczególnie na obszarach chronionych.