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Monitoring of fluvial transport in small upland catchments – methods and preliminary results

Monitoring transportu fluwialnego w małych zlewniach wyżynnych – metody i wstępne wyniki

Keywords: rainstorms, sediment transport, small catchments, Polish Uplands
Słowa kluczowe: gwałtowne ulewy, transport fluwialny, małe zlewnie, Wyżyny Polskie

INTRODUCTION

In April 2011 a study was initiated, financed from resources of the Polish National Science Centre, entitled: 'Rainstorm prediction and mathematic modelling of their environmental and social-economical effects' (No. NN/306571640). The study, implemented by a Polish-American team, covers meteorological research, including: (1) monitoring of single cell storms developing in various synoptic situations, (2) detection of their movement courses, and (3) estimation of parameters of their rain field. Empirical studies, including hydrological and geomorphological measurements, are conducted in objects researched thoroughly in physiographic terms (experimental catchments) in the Lublin region (SE Poland), distinguished by high frequency of occurrence of the events described. For comparative purposes, studies are also carried out on selected model areas in the lower course of the Mississippi River valley (USA), in a region with high frequency of summer rainstorms. For detailed studies on sediment transport processes during rainstorm events, catchments of low hydrological rank and their sub-catchments in a cascade system were selected. For the basic, relatively uniform geomorphological units distinguished this way, erosion and deposition balance of material transported was determined.

The aim of work was to determine influence of weather condition on fluvial transport rate in small catchment with low hydrological order.

METHODS

Basic research conducted in selected experimental catchments in the Lublin region included hydro-meteorological measurements and measurements of individual fluvial transport components. For the purposes of the project, a network of field stations and hydro-meteorological sites was developed (Fig. 1). The Meteorological Observatory of the Maria Curie-Skłodowska University in Lublin (UMCS) was selected as the benchmark station (173 m a.s.l.). The UMCS Observatory provides electronic recording, in accordance with the WMO standard, of the following weather elements: air temperature (at a height of 5 and 200 cm a.g.l.), ground temperature (at depths of 0, 5, 10, 20, 50, and 100 cm), precipitation, atmospheric pressure, wind velocity and direction, cloudiness, horizontal visibility, total radiation, diffuse radiation, UV-A and UV-B radiation, and solar radiation. The gauges installed are operated by an automatic A-Ster meteorological station. Measurements are performed with 10-minute temporal resolution (144 measurements per day).

The network includes the existing UMCS meteorological stations and those installed for the purposes of the project (Fig. 1):

1. Guciów site: measurement of temperature, air humidity at heights of 5 and 200 cm a.g.l., ground temperature (at depths of 0, 5, 10, 20, 50, and 100 cm), precipitation, atmospheric pressure, wind velocity and direction, and total radiation;

2. Zwierzyniec-Florianka site: measurement of temperature, air humidity at a height of 200 cm a.g.l., air temperature (at heights of 5, 20, 50, and 100 cm a.g.l.), ground temperature (at depths of 0, 5, 10, 20, 50, and 100 cm), precipitation, and wind velocity and direction;

3. Janów Lubelski site: measurement of temperature and air humidity at a height of 200 cm a.g.l. and precipitation;

4. Gutanów site: measurement of air temperature and humidity at a height of 200 cm a.g.l., and precipitation;

5. Dominikanówka site: measurement of air temperature and humidity at a height of 200 cm a.g.l., and precipitation.

Additional precipitation stations equipped with automated digital rain gauges (A-Ster) were established in the following test catchments (Fig. 1): Karmanowice (*A1*), Gutanów (*B*), Skrzynice (*C*), Kłodnica (*D*), Szastarka (*E*), and Polany (*G11*). Precipitation rate was measured at the stations with a temporal resolution of 1 minute. For a more detailed spatial analysis of precipitation rate and structure, inclusion of available satellite data (METEOSAT, EOS – Terra and Aqua) is also planned.

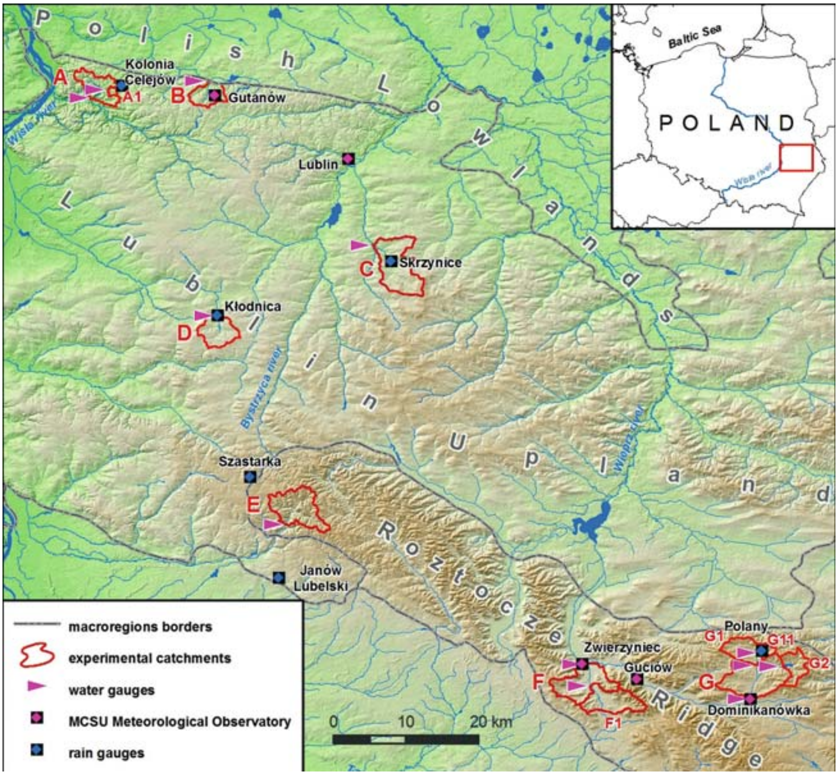

Fig. 1. Distribution of the measurement network and location of test catchments in relation to the digital elevation model (DEM) (grid 30 m): A – Stok stream, A1 – Kolonia Celejów gully catchment with periodical runoff, B – Gutanów stream, C – Skrzyniczanka stream, D – upper Chodelka stream, E – upper Sanna stream, F – Świerszcz stream, F1 – upper Świerszcz stream, G – Kryniczanka stream, G1 – upper Kryniczanka stream, G11 and G2 – Kryniczanka stream subcatchments with episodic runoff

Fluvial transport monitoring covers cyclical measurements of water stages and flow velocity in 12 representative cross-sections in catchments with permanent, periodical, or episodic runoff (Fig. 1). The monitoring network includes the already existing monitored cross-sections (A1, F, F1, G) and 8 newly-established ones. Water stages and water temperature are recorded in a one-hour cycle by means of electronic pressure limnigraphs (CTD Diver type), and by means of water-gauges and digital water-level recorders (THALIMEDES by OTT) in cross-sections functioning earlier. Water stages are also controlled with the application of staff gauges (readings every 7 days). Once a month, in field conditions, hydrometric measurements of temperature, *pH*, and water electrolytic conductivity are performed by means of Slandi electronic sensors (TC 204 thermometer, pH 204 pH-meter, CM 204 conductometer). Measurements of discharge and flow velocity distribution in the channels are also performed every 30 days by means of a hydrometric current meter (HEGA type). Additionally, catchments with periodical and episodic runoff (A1, E1, G11) are closed with installed Thompson's weirs.

Bedload measurements at low-energy discharges are performed once a month with the application of PIHM type C samplers, with 30-minute sampling time. Water samples for sediment concentration and total mineralisation analyses are taken once a week by means of a bottle bathymeter (1 dm^3) at half the depth of the main stream. At the laboratory of the UMCS Roztocze Research Station in Guciów, suspension volume is determined with the application of Brański's gravimetric method (Brański 1968) using cellulose acetate filters of medium permeability. Water mineralisation is measured by the conductometric method following Markowicz, Pulina (1979). Macroelements and heavy metal concentration are estimated by the titration method. For estimation of suspended material load, power functions were applied, calculated from correlations between discharge and turbidity. Discharge rate was calculated by the accounting method of the Institute of Meteorology and Water Management (IMGW).

Conversion of water stages to discharges was carried out based on flow rate tables. During rapid overland flows, frequency of hydrometric and fluvial transport measurements is adjusted to the intensity of the event. The measurement frequency and term depend on the course of the flood wave. Fluvial transport balance is determined based on estimation of mutual relations between its individual components – dissolved material (total mineralisation), suspended material, and bedload – in individual months and hydrological years (November–October).

Full data from new catchments are not available, even for the summer season 2011; therefore, results of the study for this season were presented from two comparative catchments, monitored earlier: the Świerszcz (*F*) and Kryniczanka streams catchments (*G*).

STUDY AREA AND SELECTED EXPERIMENTAL CATCHMENTS

Study area

The eastern part of the Polish Uplands is located between large transit rivers, the Vistula and Bug rivers (Fig. 1). It covers the Lublin Upland and parts of Roztocze, the Volhynia (Wołyń) Upland, and Pobuże. In tectonic terms it is a fragment of the Metacarpathian high, elevated during the Alpine folding, cutting through older, stable tectonic structures of the marginal zone of the East European craton. The height of the plateaus grows from 190 m a.s.l. in the north-western part of the Lublin Upland to 390 m a.s.l. on the border area of Roztocze (Buraczyński 1997).

The climate of the eastern part of the Polish Uplands has features of a transitional temperate climate. Mean temperature in January is approx. –4°C, in July approx. 18°C, with an annual mean of approx. 7.5°C. Annual precipitation total is quite varied, and amounts to 550–700 mm. Precipitation is the most abundant in summer, averaging 70–100 mm for July. The highest mean number of days with snow cover (90) occurs in the southern part of the region (Roztocze). The maximum thickness of snow cover amounts to 20–50 cm, and snow-water equivalent at the end of winter reaching 40–60 mm, and sometimes 100 mm (Kaszewski 2008).

Specific runoff is also varied at the regional scale. It is the highest (7–8 10^{-3} $m^3 \cdot s^{-1} \cdot km^{-2}$) in the most elevated southern areas of the Lublin Upland and Roztocze, where the highest annual precipitation totals occur. It is significantly lower (3–4 10^{-3} $m^3 \cdot s^{-1} \cdot km^{-2}$) in the northern part of the Lublin Upland. Rivers with a groundwater/snow-melt/rain runoff regime usually develop one snow-melt flood (March-April), and sometimes also a secondary, rainfall-driven flood, usually occurring in July. The river network is scarce due to high soil permeability, and the relief is dominated by dry valley systems (Michalczyk 1986; Rodzik et al. 2008).

High differentiation of environmental conditions and varied land cover result in the occurrence of a high number of physiographic boundaries and a specific patchwork of natural landscapes. Currently, agricultural land occupies approx. 70% of the area. The agricultural land is dominated by arable fields (65%), and the cultivation structure by cereals, with significant contribution of root crops (potatoes and sugar beets). The majority of land (approx. 90%) belongs to individual farmers, usually owning small and scattered agricultural farms (averaging 7.6 ha); therefore, a typical feature of the landscape is a patchwork of fields. Due to intensive agricultural use, large environmental contrasts, and rapid changes in the land use structure occurring after 1989, the rate of water erosion of soils in the region described is very high, particularly during violent rainstorms and spring snowmelts (Rodzik et al. 1998, 2008; Rodzik, Janicki 2003; Janicki et al. 2010).

Extreme rainfall and torrential overland flows

The Lublin region is distinguished by a frequent occurrence of intensive showers (violent rainfalls), often accompanied by hail and strong wind. The rain showers occur from April to September, with the highest frequency from May to July. The precipitation rate can exceed 20–30 mm within 15–30 minutes or 80 mm within 60–120 minutes. Rainstorms with a rate of 20–30 $mm \cdot h^{-1}$ are recorded almost annually, and those with a rate of >50 $mm \cdot h^{-1}$ every ten years on the average. Precipitation with the highest intensity (~100 $mm \cdot h^{-1}$) occurs on small areas of <100 km^2. The accompanying surface runoff reaches extreme values (>10 $m^3 \cdot s^{-1} \cdot km^{-2}$). High-intensity rainfall events also cause overland flows of several meters on small rivers, often with catastrophic results (Rodzik et al.

1998; Rodzik, Janicki 2003; Świeca, Kociuba 2007; Rodzik et al. 2008; Janicki et al. 2010).

In the area described intensive snow-melts also occur, usually in the second half of March or at the beginning of April, with water runoff of 25–75 mm. Snow-melt events also result in surface runoff lasting for several days, causing erosion of arable fields at bottoms of basins and dry valleys, and piping processes on slopes of loess gullies. Runoff concentration in beds of river valleys results in overland flows, sometimes with catastrophic economic effects (Rodzik et al. 1998; Rodzik, Janicki 2003). Somewhat smaller snow-melts (runoffs of 10–20 mm) occur every several years, for the last time in 2003 and 2006. Runoff due to snow-melt usually causes local flooding and inundation of arable fields and agricultural farms located in the zone of alluvial fans, at mouths of dry valleys, and gullies. Floods are typical of large river valleys, and are particularly dangerous within urban areas due to impermeable surfaces and modified catchments leading to rapid and extreme runoff. In Lublin, for example, they are one of the most frequent reasons for interventions of fire fighting brigades throughout the year.

Description of selected experimental catchments

The Świerszcz stream catchment (A = 45.9 km^2) is located in the southern part of the Lublin region (Fig. 1), with denivelations of > 140 m (Buraczyński 1997) within a wide tectonic depression filled with Quaternary sandy sediments (>50% of the catchment area). Slopes of the valley and the plateaus are composed of Upper Cretaceous gazies (spongolite) and opokas (>40%). Forests, mainly belonging to the Roztocze National Park, occupy 61% of the catchment, and arable land, currently largely uncultivated, only 33%. Forest ponds constitute >2% of the catchment area (Świeca 2004).

The Świerszcz stream is groundwater/snow-melt/rain-fed. This is manifested by relatively low variability of discharges and occurrence of several overland flows in a hydrological year. Total runoff ranged between 63.2 and 104.5 mm (average of 86 mm), and constituted 9–14% of the annual precipitation total. Mean annual discharge of this stream amounts to 0.13 $m^3 \cdot s^{-1}$ ($q = 2.7 \cdot 10^{-3}\ m^3 \cdot s^{-1} \cdot km^{-2}$). Extreme daily discharge values varied from $30 \cdot 10^{-3}\ m^3 \cdot s^{-1}$ to 0.63 $m^3 \cdot s^{-1}$, and values of specific runoff from $0.65 \cdot 10^{-3}\ m^3 \cdot s^{-1} \cdot km^{-2}$ to $13.7 \cdot 10^{-3}\ m^3 \cdot s^{-1} \cdot km^{-2}$ (Rodzik, Stępniewski 2008; Stępniewska, Stępniewski 2008).

The Kryniczanka stream catchment (A = 67.9 km^2) is located in the central part of the Roztocze Ridge (Fig. 1). The stream, straight and regulated, flows out of a retention reservoir located in the upper part of a former lake and is dissected by a network of ditches in the bed of a tectonic basin with a system of extensive, flat, and marshy valleys (Buraczyński 1997). Relative relief reaches up to 82.1 m (344.6–262.5 m a.s.l.), while mean inclination is minimal, amounting to approx.

2.5º. Beds of basins and valleys are filled with Quaternary sandy-silty sediments (9%). Their slopes and plateaus are composed of Upper Cretaceous sediments (opokas and marly limestones), covered in the northern and eastern part by loesses (approx. 60%). The catchment is under intensive agricultural use, with forests constituting only 12% of the total area. Arable land occupies as much as 66.5%, and meadows almost 16%. Multi-annual mean daily discharges range between 0.01 and 3.14 $m^3 \cdot s^{-1}$, and specific runoff between $0.15 \cdot 10^{-3}$ and $5 \cdot 10^{-3}$ $m^3 \cdot s^{-1} \cdot km^{-2}$. Mean surface runoff for the Krynicznka stream amounts to 98.8 mm, which constitutes approx. 15% of the annual average precipitation (2001–2003) (Świeca, Kociuba 2007).

PRELIMINARY RESULTS

Meteorological conditions in the 2011 summer hydrological season

During the research from 1 May to 31 October 2011, total precipitation reached 364.8 mm, and slightly exceeded the multi-annual mean for the summer season (440 mm). Precipitation of this season constituted approx. 83% of the annual precipitation total for 2011 (440.7 mm – after automated digital rain gauges), and approx. 73% of the mean annual precipitation total (658.4 mm) calculated for the period 2001–2003 (Kaszewski 2008). July was particularly abundant in precipitation (173.2 mm), while no precipitation was recorded in November. Rainfall in July constituted 47.5% of the precipitation total in the season analysed. A total of 87 days with precipitation of > 0.1 mm were recorded, and the maximum daily value did not exceed 40 mm (Fig. 2). Also, the temperature conditions were highly variable, with mean daily air temperatures ranging between 6.6ºC and 17.9ºC, averaging 14.3ºC (Fig. 2). The 2011 hydrological season was therefore quite warm and dry, but was simultaneously distinguished by a high variability of temperature and precipitation conditions, which is a feature typical of this region (Świeca 2004).

Variability and differentiation of discharges in selected experimental catchments (May–October 2011)

Total runoff in the period May–October 2011 from the Świerszcz stream catchment varied from 6.4 mm, which constitutes 1.8% of the precipitation total. Mean monthly values of water runoff from the catchment were quite varied, from 0.9 to 1.3 mm. Extreme daily discharge values ranged from 0.135 $m^3 \cdot s^{-1}$ to 0.498 $m^3 \cdot s^{-1}$ (Fig. 3), and specific runoff values from 0.029^{-1} to 0.109 $m^3 \cdot s^{-1} \cdot km^{-2}$. The highest mean monthly discharge was recorded in August (0.235 $m^3 \cdot s^{-1}$) and the lowest in September (0.153 $m^3 \cdot s^{-1}$), with a mean of 0.185 $m^3 \cdot s^{-1}$. The obtained maximum daily and monthly discharge values are

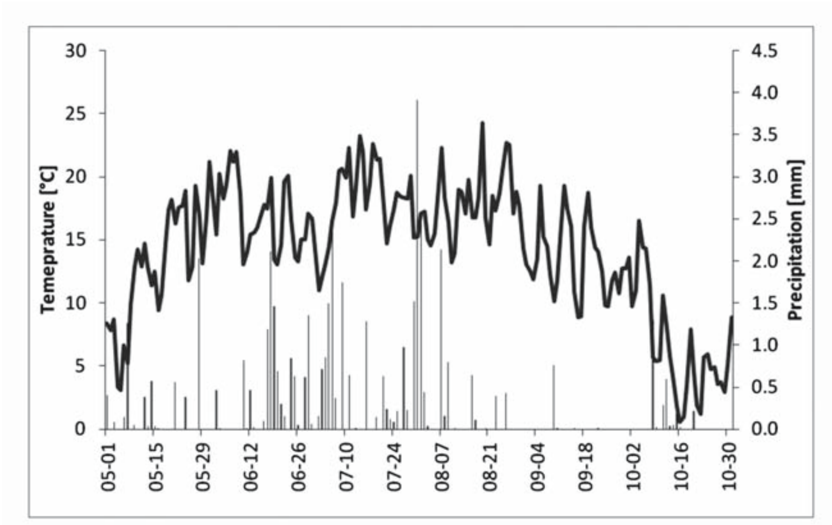

Fig. 2. Comparison of changes in mean daily air temperature and daily precipitation total in the Guciów station (Roztocze Ridge) in the period from May to October 2011

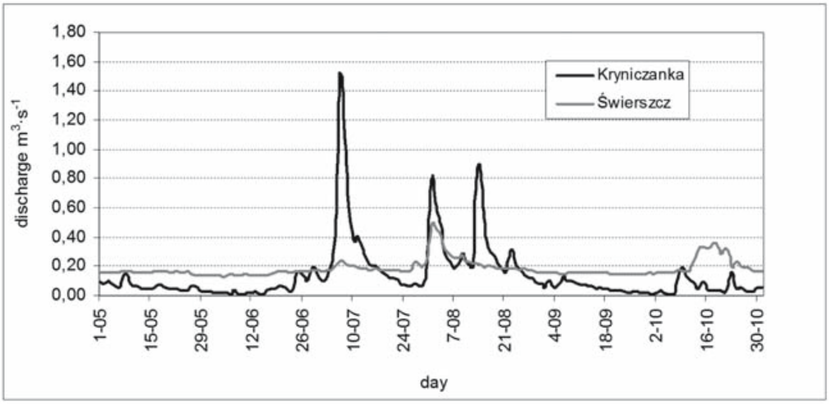

Fig. 3. Hydrograph of mean daily discharges in the streams: Świerszcz and Kryniczanka in the period from May to October 2011

comparable with maximum discharges calculated for snow-melt overland flows (Świeca, Kociuba 2007; Rodzik, Stępniewski 2008; Stępniewska, Stępniewski 2008).

In the Kryniczanka stream catchment during the period analysed the runoff coefficients were significantly lower than for the Świerszcz stream catchment. Mean surface runoff for the Kryniczanka stream catchment amounted to 10.4 mm, which constituted approx. 2.2% of the precipitation total. Extreme daily discharge values ranged from 0.013 to 1.52 $m^3 \cdot s^{-1}$ (Fig. 3), and specific runoff from 0.19 10^{-3} $m^3 \cdot s^{-1} \cdot km^{-2}$ to 0.225 $m^3 \cdot s^{-1} \cdot km^{-2}$. Those values can be compared to snowmelt overland flows recorded in the years 2001–2003 (Świeca 1998, 2004; Świeca, Kociuba 2007).

Variability and differentiation of fluvial transport in the Świerszcz and Kryniczanka streams catchments (May–October 2011)

Mean monthly total mineralisation values showed little variability, both for the Kryniczanka (231–287 $mg \cdot dm^{-3}$), and Świerszcz streams (137–177 $mg \cdot dm^{-3}$). The lowest amount of dissolved material (Kryniczanka – 38.7 t, Świerszcz – 70.1 t) was discharged in June, and the highest in July (Kryniczanka – 236.4 t), and in October (Świerszcz – 99.8 t). Total runoff of material from the catchment reached approx. 591.2 t (Kryniczanka) and 470.1 t (Świerszcz). Similar variability was reached by the contribution of suspended material in both streams, and mean monthly turbidity varied significantly (Fig. 4). In August, a maximum of 7.3 mg dm^{-3} of suspended material was recorded in the Kryniczanka stream (mean of 2.9 mg dm^{-3}), while in the Świerszcz stream, a maximum of 15.6 mg dm^{-3} was recorded in September (mean of 7.26 mg dm^{-3}). The least amount of suspended material was discharged in August in the Kryniczanka stream (approx. 6 t) and in September in the Świerszcz stream (approx. 6.2 t), primarily as a result of atmospheric drought causing low discharges. Mean monthly runoff of suspended solids amounted to 1.5 t (Kryniczanka) and 3.3 t (Świerszcz).

The contribution of dissolved material in total fluvial transport amounted to 99.7% for the Kryniczanka catchment, and 96% for the Świerszcz catchment. Contribution of bedload in transport in both streams in the period analysed was

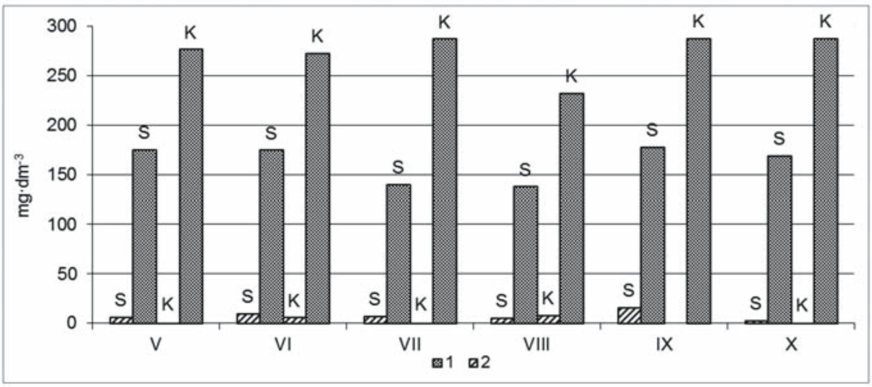

Fig. 4. Mean monthly dissolved (1) and suspended (2) material concentration in the Kryniczanka stream (*K*) and the Świerszcz stream (*S*) in the period from May to October 2011

scarce, at a level of < 1%, which is in accordance with results of earlier studies. The coefficients are similar to those from the period 2001–2003 (Świeca, Kociuba 2007).

DISCUSSION AND CONCLUSIONS

Specific denudation rates in the period May–October 2011 varied from 0.6 to 3.5 $t \cdot km^{-2}$ for the Kryniczanka stream catchment in Dominikanówka and from 1.6 to 2.2 $t \cdot km^{-2}$ for the Świerszcz stream catchment in Zwierzyniec. Mean chemical denudation rate amounted 1.5 $t \cdot km^{-2}$ for the Kryniczanka stream catchment and 0.19 $t \cdot km^{-2}$ for the Świerszcz stream catchment. Mean mechanical denudation rate amounted only 0.019 $t \cdot km^{-2}$ for the Kryniczanka stream and 0.072 $t \cdot km^{-2}$ for the Świerszcz stream. The obtained denudation rates are similar to multi-annual mean values (Rodzik et al. 2007).

Simultaneously, the rates are lower than mean values for the remaining parts of the Polish Uplands (Ciupa 1991; Maruszczak et al. 1992; Świeca 1998), and comparable with denudation rates in the area of the Central European Plain (Kostrzewski et al. 1994; Smolska 1996). This is influenced by relatively low permeability of the majority of material in the bedrock, a significant contribution of forests in land use, the buffer role of meadows in valley beds, and various forms of environmental protection, all resulting in low anthropopressure (Kostrzewski et al. 1994; Smolska 1996; Brandt 1998; Meybeck et al. 2003; Rodzik et al. 2007, 2009).

Exceptionally low mineralisation as for an upland river, recorded in the Świerszcz stream catchment, is determined by low solubility of rocks in the catchment. Seasonal variability of fluvial transport in the selected experimental catchments is directly dependent on runoff rate and distribution, reaching the highest values in July (Kryniczanka) and August (Świerszcz), and the lowest values in June and September for both catchments.

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STRESZCZENIE

W 2011 roku uruchomiono na Wyżnie Lubelskiej i Roztoczu monitoring hydro-meteorologiczny i geomorfologiczny w 7 zlewniach niskiej rangi hydrologicznej (ryc. 1), w ramach projektu NCN, pt.: „Predykcja gwałtownych ulew i modelowanie matematyczne ich skutków środowiskowych i społeczno-ekonomicznych" (nr NN/306571640). Pomiary transportu fluwialnego wykonuje się w 12 reprezentatywnych przekrojach poprzecznych rzek i potoków okresowych (ryc. 1).

W pracy przedstawiono wstępne wyniki otrzymane dla okresu maj–październik 2011 roku dla dwóch zlewni (Świerszcza i Kryniczanki) położonych na Roztoczu. W analizowanym dość ciepłym

i suchym okresie zarejestrowano 87 dni z opadem > 0,1 mm, a maksymalny opad dobowy nie przekroczył 40 mm (ryc. 2). Odpływ całkowity ze zlewni Świerszcza wahał się od 6,4 mm do 104,5 mm, co stanowiło 1,8 % całkowitej sumy opadów. Średni odpływ ze zlewni Kryniczanki osiągnął 10,4 mm (ok. 2,2% całkowitej sumy opadów). Skrajne wielkości dobowe przepływu w Świerszczu zmieniały się od 0,135 $m^3 \cdot s^{-1}$ do 0,498 $m^3 \cdot s^{-1}$ (ryc. 3). Najwyższe przepływy miesięczne przypadały na sierpień (0,235 $m^3 \cdot s^{-1}$), najniższe na wrzesień (0,153 $m^3 \cdot s^{-1}$). W Kryniczance skrajne wielkości dobowe przepływu zmieniały się od 0,013 do 1,52 $m^3 \cdot s^{-1}$, natomiast najwyższe przepływy zanotowano w lipcu, a najniższe w czerwcu i październiku (ryc. 3).

Średnie miesięczne wielkości mineralizacji całkowitej były mało zmienne, zarówno dla Kryniczanki (231–287 $mg \cdot dm^{-3}$), jak i Świerszcza (137–177 $mg \cdot dm^{-3}$). Najmniej roztworów odprowadzanych było w czerwcu (Kryniczanka – 38,7 t, Świerszcz – 70,1 t), najwięcej w lipcu (Kryniczanka – 236 t) lub październiku (Świerszcz – 99 t), a całkowity odpływ materiału ze zlewni osiągnął 591 t (Kryniczanka) i 470 t (Świerszcz). Udział materiału rozpuszczonego w całkowitym transporcie rzeczym był bardzo wysoki (do 99.7%), a materiału dennego niewielki (< 1%).

Wskaźniki denudacji jednostkowej w okresie maj–październik 2011 roku wahały się od 0,6 do 3,5 $t \cdot km^{-2}$ dla zlewni Kryniczanki oraz od 1,7 do 2,2 $t \cdot km^{-2}$ dla zlewni Świerszcza. Średnie wskaźniki denudacji chemicznej osiągnęły 1,5 $t \cdot km^{-2}$ dla Kryniczanki i 0,19 $t \cdot km^{-2}$ dla Świerszcza. Średnie wskaźniki denudacji mechanicznej dochodziły do 0,019 $t \cdot km^{-2}$ dla Kryniczanki i 0,072 $t \cdot km^{-2}$ dla Świerszcza. Otrzymane wskaźniki denudacji nie odbiegają od średnich z wielolecia.

Zróżnicowanie transportu fluwialnego w analizowanych zlewniach było uzależnione od wielkości i rozkładu odpływu oraz pokrycia terenu. Otrzymane zaś wskaźniki denudacji są niższe od przeciętnych dla Wyżyn Polskich i porównywalnie z obszarami Niżu Środkowoeuropejskiego. Wpływa na to stosunkowo mała rozpuszczalność większości skał w podłożu, znaczny udział lasów i łąk w dnach dolin oraz małe nasilenie antropopresji (duży udział obszarów chronionych).