STUDY OF HEAVY RAINS IN URBAN AREAS ON THE EXAMPLE OF BRNO, CZECH REPUBLIC

GRAŽYNA KNOZOVÁ, MARIE DOLEŽELOVÁ
Czech Hydrometeorological Institute, Brno Regional Office, Kroftova 43, 616 67 Brno, Czech Republic

The paper focuses on heavy rains in Brno agglomeration, the second largest urban area in the Czech Republic. Extreme precipitation events were studied with the help of 1-minute precipitation amounts measured at three urban sites in Brno city and one site in surrounding rural region. Additionally, data from nine Hellmann rain gauges from Brno and its surroundings were used. Occurrence of torrential rains was evaluated according to Wussow's method that distinguishes between downpour, strong downpour and catastrophic downpour (Wussov, 1922). It was found that torrential rains in the studied area occur usually in the period from April to November. The 15-year long observation of the phenomenon at Brno-Žabovřesky station shows varying frequency – from none in 2007 to four in 2004 and 2010. Strong downpour on 31 July 2014 was one of the heaviest rains ever observed in Brno when daily precipitation sums at particular stations reached values up to 88.9 mm. This rain caused considerable damage in central part of the city. Moreover, following torrential rain in Brno area occurred only three days later, and then it occurred again twice in two weeks in the surroundings of the city. Very wet weather presented considerable complications for city transport (state of roads and tramlines). The phenomenon of torrential rains repetition in short time is caused by specific meteorological conditions favourable to convective weather conditions. Such situations represent remarkable problem for densely populated urban areas because of their economic consequences.

Keywords: urban climate, precipitation, downpour, rainfall intensity, extreme weather, Brno, Czech Republic

INTRODUCTION

Precipitation and especially heavy rainfall represent one of the most important issues in urban climatology. As they can cause local flooding, extreme weather events have big impact in densely populated urban areas. Downpours, defined as rains of high intensity and short duration, though very local, can have very dramatic and costly consequences. For example, on July 31, 2014 the extreme precipitation caused a blockage of sewage system, roadways inundation and damaged several buildings within Brno city. Repetitive torrential rains in summer 2014 resulted in various complications in transportation and damage in construction industry.

In the context of anticipated climatic changes, an increase in precipitation sums and change in the seasonal distribution of precipitation is expected (Brázdil et al., 2007). While evaluating precipitation, extremity indexes based on daily rainfall totals are used in most climatological works (e.g. Doleželová, Knozová, 2013). Researching the rainfall intensities requires a more detailed study material containing hour and minute precipitation amounts, depending on the methodology used.

Criteria for the evaluation of torrential rains can differ substantially. For example, according to Hellmann, torrential rain is a rain with precipitation sum between 10 mm and 80 mm in period shorter than 180 minutes (Sobíšek et al., 1993). According to Chomicz, we call the rain as torrential in case that the rainfall reaches at least 12.8 mm in 10 minutes (Niedźwiedź et al., 2003). Wussow's method (Wussow G. 1922; ČHMÚ, 1988) is most commonly used in the Czech Republic. Torrential rain is here defined by lower limit value of precipitation sum over a specific time expressed in minutes. The limit value is determined on the basis of empirical formula and the method distinguishes between three types of torrential rains – downpour (less severe), strong downpour and catastrophic downpour (most severe).

Torrential rains usually affect an area spanning from a few to several tens of square kilometres and occasionally hundreds of square kilometres. With a varying intensity, they may last from several minutes to several hours. In Central Europe, their occurrence is limited mainly to the warm season – i.e. April to October (Dimitrova, T. et al., 2009; Knozova, 2014 a). Occurrence of heavy rains is caused by the convection phenomena. In storms and during the transition of atmospheric fronts, rainfall reaches the highest intensity. According to Řezáčová et al. (2007) the potential for torrential rain occurrence grows when a convective storm moves slowly and thus many single convective cells are allowed to reach a mature stage. Adverse effects of torrential rains depend mostly on three factors: amount of fallen water, duration and intensity of the rain. The intensities and frequencies of torrential rains are related to local and remote terrain configuration allowing frequent thunderstorms formation or regulating the frontal storms pathways. The possibility of torrential rain forecasting is very limited due to the rapid dynamics of convective clouds. Although predestinating weather conditions of heavy rains can be predicted quite successfully, precise location, duration and intensity of a torrential rain cannot be predicted with satisfactory accuracy as well as the area of eventual occurrence of flash floods (Daňhelka et al., 2015).

This study is focused on torrential rains in Brno urban area and its surroundings. Brno is a city of moderate size with about 400 000 inhabitants, covering the area of app. 230 square kilometres. As the city lies where three geomorphological units meet, its geographic conditions tent to be quite varied. The northern edge of the city lies in the Drahanská Highlands, the western part in the Bobrava Highlands and the eastern part is located in the Dyjsko-svratecký Valley. The altitude of urban area ranges values between 190 m a.s.l. and 479 m a.s.l. and this range significantly affects climatic conditions of the city (Dobrovolný et al., 2009).

The aim of the study is to analyse the occurrence of torrential rains in Brno urban area in the period 2010−2014. Special attention is paid to case study of the event on 31 July 2014. Conclusions are formulated in the context of urbanization's impact on precipitation conditions on a regional scale.

MATERIALS AND METHODS

Daily precipitation sums measured at six meteorological stations of the Czech Hydrometeorological Institute (CHMI) were used as a basic data source. Three stations represent the urban environment (Brno-Žabovřesky, Brno-Jundrov and Brno-Židenice) while two other stations represent the suburban climate (Brno-Tuřany and Troubsko) and the last one is located outside the urban area in Drahanská Highlands (Bukovinka). Furthermore, for the purpose of spatial analysis data from seven remote locations were used.

Rainfall intensities were evaluated with the help of 1-minute precipitation sums measured by automatic tipping-bucket rain gauge at four CHMI's sites. Analysis of selected cases were performed using radar reflectivity data from CZRAD network as well as the observations of various atmospheric phenomena. It should be noted that the materials used are not quite complete, mostly due to technical problems. Intense rains are often accompanied by extreme weather phenomena, such as lightning or strong winds, which can cause disruption of measuring device or clogging of tipping-bucket rain gauge with mechanical impurities like leaves or twigs. All cases of detected episodes with torrential rain were therefore carefully controlled.

Intensity of precipitation was evaluated by means of the Wussow's method (Wussow, 1922), based on the definition of critical value of total precipitation amount fallen over specific time. In case of its exceeding, rain can be classified as torrential. When applied to precipitation with duration up to two hours, the formula $h \leq \sqrt{5t}$ (where h is precipitation amount in mm and t is duration of rain in minutes) indicates than the rain is not torrential. For $\sqrt{5t} < h \leq 1.5\sqrt{5t}$ rain is considered "downpour", for $1{,}5\sqrt{5t} < h \leq 2\sqrt{5t}$ "strong downpour" and for $h > 2\sqrt{5t}$ it is called "catastrophic downpour". Calculatios of maximum precipitation sums for particular durations were executed with the help of ProClimDB software (http://www.climahom.eu).

CASE STUDY OF TORRENTIAL RAIN ON 31 JULY 2014

The event of 31 July 2014 belongs to the most extreme precipitation events in Brno within the analysed period. A very intense rain caused serious traffic problems and consequential damage to property in the centre of Brno where some buildings were flooded due to the blockage of public sewers. This situation will be subjected to a detailed analysis as an example of torrential rain in urban conditions.

On 31 July 2014 a cold front was dissolving. According to the record of the weather radar and the observations done at particular sites, remote thunderstorm accompanied by rain of moderate intensity and lasting until about 3 am was recorded. Two showers passed in the morning hours and then in the afternoon a steady mild to moderate rain continued.

In the morning two episodes of rain were detected. The first episode began at about 8:40 am and lasted until 10 am. At Troubsko station rainfall intensity exceeded critical value for strong downpour with maximum value of 1.7 $mm.min^{-1}$. Within one hour, total precipitation amount reached 25.3 mm. The second episode began at 10:30 am and lasted until 2:20 pm. Precipitation had torrential character and reached the sum of 44.4 mm per 1 hour and 48 minutes at Brno-Žabovřesky site. According to the Wussow's scale it is classified as a downpour. Downpour occurred also at Brno-Tuřany site which reached total precipitation amount of 24.3 mm in 1 hour and 40 minutes (Fig. 1). Afterwards precipitation intensity started to decrease, but the rain continued till evening hours and rainfall zone was slowly moving to the northwest. Daily precipitation amount on 31 July 2014 at Brno-Žabovřesky station reached the value of 69.5 mm while highest precipitation amount within Brno urban area was measured at Brno-Jundrov site (88.9 mm). In the vicinity of Brno, rainfall totals were slightly lower but in some locations exceeded 50.0 mm (Fig. 2). This extreme situation hit even harder in the Svitavská Hills, southern Bohemia and in some areas in Austria and southern Poland (Fig. 3).

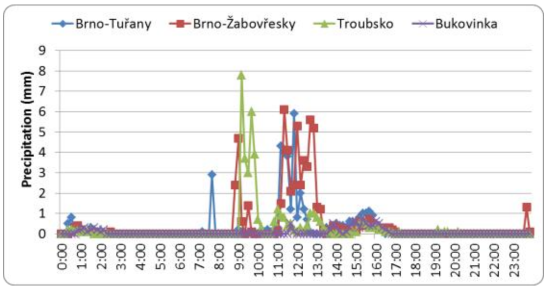

Fig. 1 The course of precipitation in Brno on 31 July 2014 at 10-minute intervals

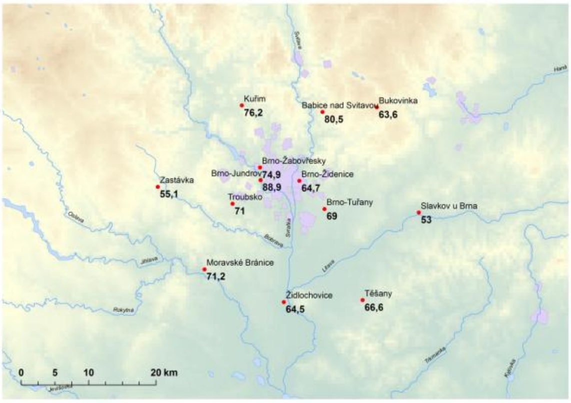

Fig. 2 Daily precipitation sums on 31 July 2014 in the Brno region

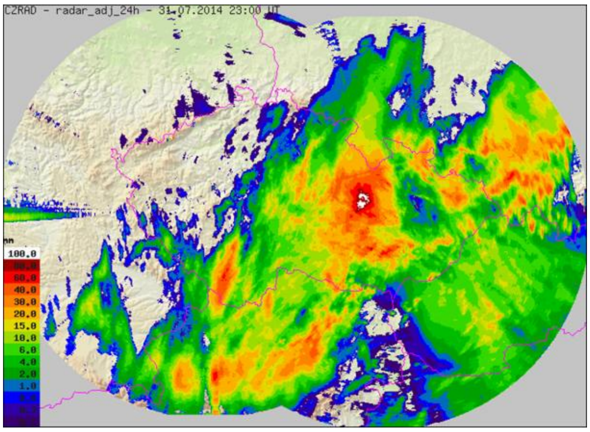

Fig. 3 Radar estimates of rainfall in 24 hours on 31 July 2014 in the Czech Republic

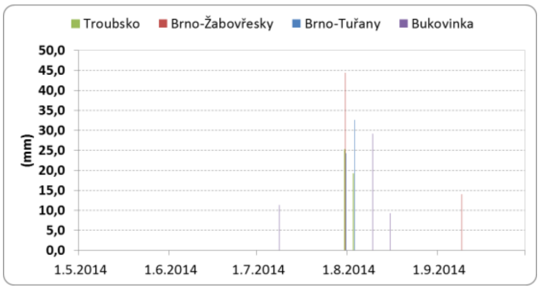

Fig. 4 Precipitation sums in torrential rains in the Brno region in 2014

The event of 31 July was followed by favourable thermal conditions for intensive evapotranspiration when moist air from the woodland area in Drahanská Highlands has contributed to the development of convective processes and thus torrential rains in the Brno region recurred on 3 August (see Fig. 4). According to Pickett et al. (2011) differences in soil moisture occur depending on different land-use and land-cover types in urban landscapes. Atmospheric moisture transport across different landscapes occurs in the boundary layer. Precipitation regime in Brno agglomeration situated between wooded highlands in the north and west and agricultural areas in the south and east is influenced by the spatial distribution of rainfall throughout the region.

SOME STATISTICAL CHARACTERISTICS OF TORRENTIAL RAINS IN BRNO REGION DURING THE PERIOD 2000–2014

Continuous measurements of precipitation in 1-minute intervals in the CHMI network have been conducted since 2000 to the present. The assessed period is thus limited to the start of automatic measurement at individual stations. Brno-Žabovřesky station has the longest time series of rainfall intensities in Brno. Its 15-year long observation shows varying frequency of torrential rains – from none in 2007 to four in 2004 and 2010. The most extreme was catastrophic downpour on 15 July 2009 (see Fig. 5) with total precipitation amount of 45.8 mm and maximum rainfall intensity of 4.1 $mm.min^{-1}$. On that day, downpour was recorded also at Brno-Tuřany site.

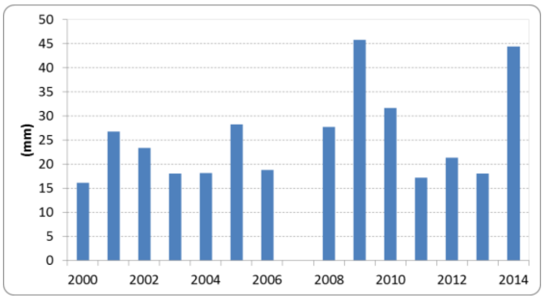

Fig. 5 Maximum precipitation amounts in the torrential rain in Brno-Žabovřesky during the period 2000 – 2014

The results of the continuous measurements between 2010 and 2014 are from four meteorological stations. The richest in the number of torrential rains was the year of 2011 when two to five episodes were reported at the individual stations (Table. 1). This year was at the same time the driest in the 15-year period with annual rainfall ranging from 351.9 mm in Troubsko to 448.9 mm in Brno-Židenice.

Table 1 Number of torrential rains in the Brno region during the period 2010−2014

Rok	Troubsko	Brno-Žabovřesky	Brno-Tuřany	Bukovinka
2010	2	4	1	3
2011	3	2	2	5
2012	2	3	2	3
2013	2	2	4	1
2014	2	2	2	3

Table 2 Maximum precipitation amounts (mm) per torrential rain in the Brno region during the period 2010−2014

Rok	Troubsko	Brno-Žabovřesky	Brno-Tuřany	Bukovinka
2010	47,0	31,6	50,9	44,0
2011	19,0	17,2	16,3	21,7
2012	20,1	21,3	16,2	30,2
2013	13,6	18,0	27,6	16,5
2014	25,2	44,4	32,6	29,1

The above mentioned period of 2010−2014 was subjected to the analysis of specific storm events. Results show that the season in which the heavy rains occur usually lasts from May to September, with lower frequency from April to October/November as documented also in some other regions (Knozová, 2014 a). During some events torrential rains can recur over several days as in the case of 31 July 2014 that was described above. There are serious consequences of such recurrences in the form of flash floods and soil erosion. The report evaluating floods in the Czech Republic in 2013 concludes that saturation of soil profile occurs already during the first torrential rain and subsequent episodes can produce disastrous consequences even when the rain is less intense (Daňhelka et al., 2014).

Regarding the daily course, torrential rains occur predominantly in the morning and afternoon hours depending on the development of convective processes in the atmospheric boundary layer. However, exceptional cases of torrential rains accompanying atmospheric front passage were observed even during evening and night hours. In many cases, rainstorms were accompanied also by the occurrence of hails (Knozová, 2014 b). The duration of torrential rains spans from few to tens of minutes.

Maximum rainfall intensities during torrential rains usually reach values of about 3 $mm.min^{-1}$ and together with event duration they affect its total precipitation amount. The most intense rainfalls occur in storms with slow motion residing in the given territory for an extended period of time or those creating more convective cells during their development (Řezáčová et al., 2007). In the studied period, torrential rains produced totals ranging from 7.3 mm to 50.9 mm (see Tab. 2). Note that these amounts were calculated only from the episodes evaluated as torrential. The torrential rain share in the daily precipitation amount varies from 40 % to 100 %.

OCCURRENCE OF TORRENTIAL RAINS IN URBAN CLIMATE CONTEXT

Urban areas have, due to a variety of geographic features, characteristics different to the countryside protected from the intense human intervention. However, in case of precipitation regime it is quite difficult to assess precisely the impact of human activities. Processes taking place around the city influence intensely changed geographical environment of Brno adjacent to the protected area of the Moravian Karst. However, there is a significant influence of urban phenomena, e.g. urban heat islands (UHI).

Air temperature in urban areas is influenced by a number of factors. Among the most important are the specific characteristics of active surfaces, including their vertical segmentation and spatial organization. The build-up area geometry is one of the main mechanisms that contribute to UHI shaping (Fortuniak, Kłysik, Wibig, 2006). Detailed analysis of Brno temperature conditions revealed that UHI peak in Brno is reached at night due to the limited long wave radiation heat loss and slower release of the stored heat (Dobrovolný et al., 2012). Another significant factor largely affecting thermal regime of a particular area is the relative topography and slope of relief. The Brno basin is open to the south and the southwest. Although plains and plateaus dominate the Brno relief, there is a relatively large area formed by gentle and steep slopes. The orientation of slopes to the south and southwest exposes the surface to sunlight and maximum air temperature in the city is higher than in its surroundings. Intense warming of the air occurs in the urban area in the afternoon and thus causes a secondary maximum of UHI. According to Dobrovolný et al. (2012), during summer, maximum air temperature in the city centre can be about 1.5 °C to 2.0 °C higher compared to the surrounding areas.

Special character of thermal conditions has considerable effect on precipitation regime. Thermal effect is considered to be the major cause of isolated rainfall over the city in summer. In this context, storms are more frequent. They are initiated by convective processes over the city and move across the urbanized area depending on the structure of buildings (Bornstein and Lin, 2000). Presence of urban surfaces causes noticeable change to the physical properties of rainfall, including the amount of fallen water, rainfall intensity and frequency or dynamic properties of storm evolutions (e.g. structures, tracks, timings) (*Yang* et al., 2013). Latest models of urban climate (De Ridder, Lauwaet, Maiheu B., 2015) consider also the impact of urban's vegetation evapotranspiration on the flow of latent heat as it contributes to the development of convective processes.

Šálek et al., (2012) performed short-term precipitation analysis using the information from the weather radar and 5, 10, 20, 30 and 60-minute precipitation sums measured in a dense network of special purpose stations that comprised 20 sites. It has been found that the highest precipitation amounts for 10 and 20-minute rain occur in the SW part of Brno which means the sheltered side of the city. It should be noted that the work used data from the period 2003–2009 and included all the episodes, not only torrential rain.

This work focuses mainly on the characteristics of the torrential rains occurrence in Brno. As it is based on relatively short period of 5 years, the conclusion should be formulated with caution. Analysis of 33 days with torrential rain in the period 2010−2014 revealed that rainfall is highly variable in space. In some situations, higher precipitation amounts fell within the city (e.g. on 31 July 2014), while in the other cases maximum was found in its surroundings, depending mainly on the direction of storm passage. Another example is the case of 1 June 2011 when torrential rain occurred 5 kilometres north of Brno in a thunderstorm related to a slowly moving cold front passing from the east to the west. Daily precipitation sum in this location reached 25 mm while in the city it was not more than 9 mm as the storm hit only its marginal part.

Although the influence of Brno urban area on rainfall intensities is not completely explained, it is possible to observe relatively more substantial rainfall in the central part of the city. Annual precipitation amount at 13 meteorological sites that were used in this study depends mainly on the altitude of individual sites (see Tab. 3). Somewhat exceptional in this context is Brno-Židenice station with the highest annual precipitation rainfall within the urbanized area. Beeing located near the Svitava River at an altitude of 203 m a.s.l., Brno-Židenice is one of the lowest stations. However, it is strongly influenced by local conditions (built-up area near an ancient industrial zone). For these reasons, it can be assumed that higher precipitation amount can be related to the occurrence of UHI and increased air pollution.The comparison of average daily precipitation in days with torrential rain comes to the same conclusion with highest rainfall in Brno-Židenice. However, variance in precipitation sums between particular sites is not significant. Relatively high values were recorded in the central part of the city (Brno-Jundrov and Brno-Židenice) and in the northeast suburbs (Babice nad Svitavou and Bukovinka). The lowest values occurred at Židlochovice and Těšany stations located in the southern part of the studied area in the Dyje-Svratka Valley.

Based on the results described above, it can be stated that atmospheric circulation plays essential role during the events of intense rains in Brno as is confirmed also by other studies (e.g. Lupikasza, 2010). The morphology and the character of the landscape plays important role, too. The city's influence on modification of precipitation regime is the most evident in the central part of Brno and is probably related to the presence of UHI (Dobrovolný et al., 2012). To evaluate the city's influence on the intensification of rainfall more precisely, longer time series needs to be used and thus incorporation of earlier ombrographic data would be necessary.

Tab. 3 Average annual precipitation amounts (year) and average daily precipitation amounts in the days with torrential rain (torrential days) in the Brno region in the period 2010−2014

Station	Altitude (m)	Year (mm)	Torrential days (mm)
Bukovinka	524	647,5	14,5
Babice nad Svitavou	470	625,5	14,3
Zastávka	345	557,1	13
Kuřim	291	579,9	12,3
Troubsko	278	507,5	13,2
Brno-Jundrov	260	550,5	14,7
Brno-Tuřany	241	526,5	13,3
Brno-Žabovřesky	236	540,1	13,6
Slavkov u Brna	211	565,7	10,5
Moravské Bránice	210	546,8	11,6
Těšany	209	523,3	7,8
Brno-Židenice	203	562,9	15,4
Židlochovice	183	516,9	7,6

CONCLUSION

Precipitation regime in urban areas is very important with regards to surface runoff. Due to the high portion of impermeable surfaces, surface runoff in the cities differs substantially from that in a natural environment. Impervious surfaces affect mainly the speed and height of the drain. The main problems of the torrential rain on 31 July 2014, discussed in chapter 3, arose from the character of water runoff. Correct assessment this factor is also very important when designing the city sewer system (for Brno it was researched e.g. by Prax et al., 2010). Dealing with rainwater at construction sites is covered by legislation of the Czech Republic. Great emphasis on draining of rainwater from paved areas regards also its potential to mix with harmful substances. Another important hydrological issue is the overall deficit of water and thus the need for rainwater retention and the reuse of wastewater in the urban areas (Krátký, 2014).

Extreme rainfall plays an important role in the hydrological system of cities. The aim of the analysis presented in this paper was to characterize the frequency and intensity of heavy rains in Brno and its surroundings. Torrential rains as classified according to the Wussow's method occur in Brno in the season from May to September. Overall number of torrential episodes is not as high, but it is compensated by the fact that they can repeat in a relatively short period of time, due to specific synoptic conditions. Maximum rainfall intensity in torrential rains reaches values about 3 $mm.min^{-1}$ and the average portion of torrential rain in the daily precipitation sum is around 70 %. The results can be considered as the basis for future studies focusing on the specific characteristics of precipitation regime in urban areas.

LITERATURE

Bornstein, R.D., Lin, Q., 2000, Urban heat islands and summertime convective thunderstorms in Atlanta: three case studies, Atmos. Environ., 34: 507–516.

Brázdil, R., Kirchner, K. et al., 2007, Vybrané přírodní extrémy a jejích dopady na Moravě a ve Slezsku. Masarykova univerzita, Brno.

ČHMÚ, 1988, Zpracování klimatologických informací. Účelová neperiodická publikace ČHMÚ.

Daňhelka, J., Janál, P., Šercl, P. et al., 2015, Možnost predikce *přívalových povodní v podmínkách České republiky. Sborník prací Českého hydrometeorologického ústavu. ČHMÚ, Praha.*

Daňhelka, J., Kubát, J., Šercl, P., Čekal. R., 2014, Floods in the Czech Republic in June 2013. ČHMÚ, Prague.

De Ridder, K., Lauwaet, D., Maiheu, B., 2015, UrbClim – A fast urban boundary layer climate model. Urban Climate, 12: 21–48.

Dimitrova, T., Mitzeva R., Savtchenko, A., 2009, Environmental conditions responsible for the type of precipitation in summer convective storms over Bulgaria, Atmospheric Research, 93: 30–38.

Dobrovolný, P. et al., 2012, Klíma Brna - Víceúrovňová analýza městského klimatu. Masarykova univerzita, Brno.

Doleželová, M., Knozová, G., 2013, Investigating the extremity of precipitation regime and the occurence of downpours in the Czech Republic. Are there any alarming changes in the last decades?, [in]: Šiška B., Nejedlík P., Hájková L., Kožnárová V. (eds) Environmental changes and adaptation strategies, Conference proceedings Abstracts, 9th – 11th September 2013, Skalica, Slovakia: 13.

Fortuniak, K., Kłysik, K., Wibig, J., 2006, Urban-rural contrasts of meteorological parameters in Łódź. Theoretical and Applied Climatology, 84, 1-3: 91-101.

Knozová, G., 2014 a, Charakteristika přívalových srážek v Protivanově, Kroměříži a Vizovicích (2003-2013). Fyzickogeografický sbornik 12, MU: 85-93.

Knozová, G., 2014 b, The Occurrence of Hail in Selected Location within South Moravia Region in the Period 2003 – 2013. [in]: Rožnovský J., Litschmann, T, (eds): Mendel a bioklimatologie. Brno, 3. – 5. 9. 2014.

Krátký M., 2014. Městské odpadní vody – významný zdroj vody pro závlahy. Vodní hospodářství, 10: 21-23.

Lupikasza, E., 2010, Relationships between occurrence of high precipitation and atmospheric circulation in Poland using different classifications of circulation types. Physics and Chemistry of the Earth 35: 448–455.

Niedźwiedź, T., 2003, Słownik meteorologiczny, IMGW, Warszawa.

Pickett, S.T.A., Cadenasso, M.L., Grove, J.M., Christopher, G. Boone, Peter M. Groffman, Elena Irwin, Sujay S. Kaushal, Victoria Marshall, Brian P. McGrath, Nilon C.H., Pouyat R.V., Katalin Szlavecz, Austin Troy, Paige Warren, 2011, Urban ecological systems: Scientific foundations and a decade of progress, Journal of Environmental Management 92: 331 – 362.

Prax, P., Hradská, A., Pospíšil, O., Hellebrand R., 2010, Řešení dešťových vod v rámci generelu odvodnění města Brna. Hospodaření s dešťovými vodami ve městech a obcích, VUT Brno, FAST, Brno.

Řezáčová, D., Novák, P., Kašpar, M., Setvák, M., 2007, Fizyka oblaků a srážek. Academia, Praha.

Sobíšek, B. (ed)., 1993, Meteorologický slovník výkladový a terminologický, Praha, Ministerstvo životního prostředí ČŘ.

Šálek, M., Štěpánek, P., Zahradniček, P., 2012, Analysis of rainfall intensities using very dense network measurements and radar information for the Brno area during the period 2003-2009. Meteorologische Zeitschrift, 21, 1: 29-35.

Wussow G., 1922. Untere Grenze dichter Regenfälle. Meteorologische Zeitschrift, 39, 173–178.

Yang, L., Smith, J.A., Baeck, M.L., Bou-Zeid, E., Jessup, S.M., Tian, F., Hu, H., 2013, Impact of urbanization on heavy convective precipitation under strong large-scale forcing: a case study over the Milwaukee-lake Michigan region. J. Hydrometeorol., 15 (1): pp. 261–278.

http://www.climahom.eu