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Influence Of The Rainfall Movement On The Required Volume Of Storage Reservoirs

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INFLUENCE OF THE RAINFALL MOVEMENT ON THE REQUIRED VOLUME OF STORAGE RESERVOIRS

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Temporal and spatial variability of rainfalls have a significant impact on the operation of urban drainage systems. Stormwater storage reservoirs are particularly sensitive to these variations. This paper presents the results of research on the impact of the direction and speed of rainfall movement over an urban catchment of total area 560 ha on required volume of the storage tank. Simulations (using SWMM5 software) showed that movement of rainfall cells has a moderate impact on the peak-flows, however, significantly affect the volume of stormwater accumulated in storage tanks. The most unfavorable variant is the rainfall moving in the direction and with speed close to the general direction and average speed of stormwater flow in the drainage system. The estimated increase of the unit volume of stored stormwater resulting from the dynamic properties of rainfall is about 6.5 to 8.0 m^3 per hectare of impervious surface in comparison to static scenario.

INTRODUCTION

Since majority of rainfall measurements, apart from radar observations, supply point values while runoffs an areal process, assessments of areal rainfall values are necessary. Design storms, and even historical rainfalls used in hydrodynamic simulations, are almost always taken from one-point data (Intensity-Duration-Frequency relationships). When a design storm is applied, the movement of a storm is not considered – rainfall simply rapidly appear over whole catchment and also rapidly disappear after time t_d (rain duration). Therefore the rainfall frequency provided by IDF relationships does not correspond to the observed runoff frequency. Real rainstorms move over a catchment, and the speed and direction of the movement of a storm significantly affect the shape of the hydrograph. In urban drainage systems the storage facilities are specially sensitive for spatial variability of rainstorms because required storage volume is estimated based by calculating the differences between inflow and outflow hydrograph. Because outflow-rate (Q_0) is often assumed as constant value thus inflow hydrograph is decisive. Many hydrological studies have focused on the role of rainfall space-time variability in catchment response, with the aim of developing a rationale for more effective catchment monitoring, modelling and forecasting (e.g., Bell and Moore [1], Naden [10], Obled et al. [12], Rodriguez-Iturbe et al. [13], Morin et al. [8]). In literature only few works concernig the significance of rainfall movement for applications such as the design of stormwater drainage systems (conduits, reservoirs, CSOs etc) (Niemczynowicz and Bengtsson [10, 11], Bursztа-Adamiak and Mrowiec [4], Borga et al. [3], Vaes et al. [17]). Abovementioned studies emphasized impact of local climatic conditions (i.e. predominant directions of wind, annual precipitation depth) on characteristics of rainfalls (duration, range, max. intensities etc.) (Bergue et al. [2]).

In most hydrological calculations we are dealing with inadequate and insufficient rainfall data (temporal resolution, spatial resolution, duration of collected data). Rigorous requirements of space and time resolution of gauge network that would resolve spatial and temporal variability of the convective rainfall process can, for practical reasons, never be satisfying (Schilling [14], Zocatelli et al. [18]). Radar and satellite measurements still give rough measures of rain intensities (Krajewski and Smith [7]). For these reasons the article attempts to assess the impact of dynamic properties of rainstorms on sizing storage tanks using IDF relationship and available software.

RESEARCH METHODS

Description of hydrodynamic model

Examination of the impact of the rainfall on drainage systems based on a hydrodynamic model of large urban catchment located in the central part of Czestochowa. The total area of the catchment (560ha) was divided into 200 subcatchments based on a Digital Elevation Model with a resolution of 5 meters. Model of drainage network includes of 415 conduits, 410 nodes, and the total length of 34.5 km. Maximum outflow-rates from the catchment reach over 10 m^3/s for intensive rainfalls.

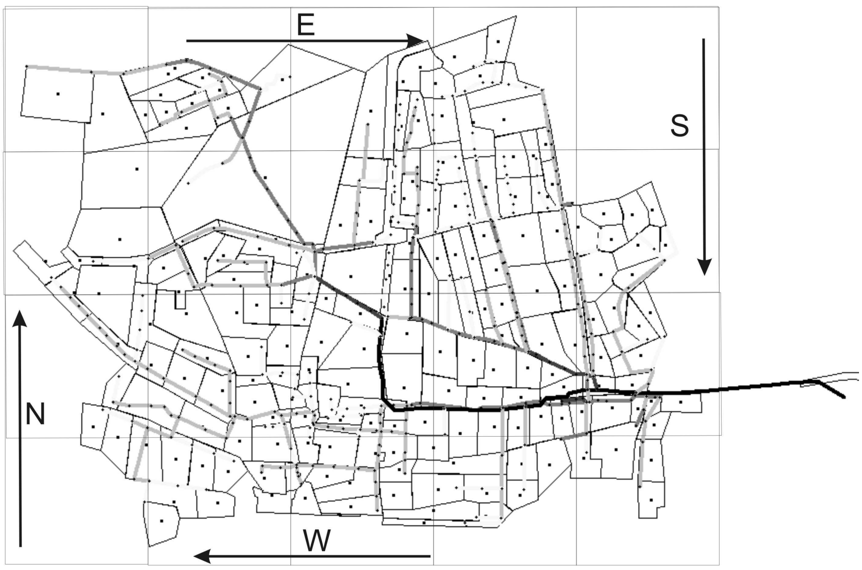

Figure 1. Scheme of modeled catchment divided on 200 subcatchemnts. Whole area divided into 16 sectors (dimensions 600x600m), which are the basis for simulation of rainfall movement over the catchment in four general directions (N, E, S, W).

The presented model has been calibrated in terms of the transformation of intensive rainfall to runoff from the catchment taking into account 21 rainfall events recorded at 5 raingauges during 2007÷2008 years. The flow-rates in channels was measured using PCMPro flow meter (flow velocity is calculated using interrelation between two similar image patterns). Flow-rates were measured at 4 locations (12 events were measured at outlet of the drainage system). Average value of relative error regarding stormwater volume was equal to 5.5% (for outlet cross-section it was 7.2%), for particular events it was ranged from 2.7 to 24.7%. Good agreement between observed and measured values is mainly resulted by application of 5 raingauges (Clemens [5]). Obtained results confirm the hydrodynamic model correctly reflects rainfall-runoff process and unsteady flow through the complex drainage network.

Rainfall data

Because SWMM5 software do not contain a routine for direct simulating moving rainstorms, therefore whole area was divided into a sectors of dimensions 600×600m (fig. 2). Each sector had its own raingauge, so it was possible to assign hyetographs with appropriate time shift. Rainfall movement was simulated by lagging the uniformly distributed rainfall stepwise over the subcatchments, with a time shift chosen in accordance with required storm velocity. For given rainfall velocities v_r=2 m/s; 5 m/s and 10 m/s the time of rain cell travelling over the sector is equal 5min, 2min, and 1 min respectively. Figure 2 presents the difference between given representation of rainfall movement (rainfall of duration t_d=20min, moving in east direction at velocity 5m/s) with traditional static representation of rainfall. Paradoxically, although the traditional approach is in literature called a "static", in a physical sense, the velocity of rainfall movement over the catchment is so high that the time shift between sectors is zero (the velocity is infinitely high) - hence the static variant is marked as $v_r = \infty$.

It was necessary to detrmine relationship between intensity of rainfall and its duration for given return period (2 years). Currently, the most commonly used IDF equation in Poland is developed by Institute of Meteorology and Water Management. Precipitation data recorded during years 1960-1990 on 20 meteorogical stations in Poland makes possible to describe IDF relationship as (Mrowiec 2013):

$$P = 1,42 \cdot t_d^{0,33} + \alpha\left(-\ln p\right)^{0,548} \quad [\mathrm{mm}] \tag{1}$$

where: t_d – rain duration [min]

p – probability of occurrence,

α - geographical coefficient.

It should be emphasized that regardless of the adopted velocity and direction of rainstorm movement the total volume of water falling on the catchment is identical to static variant (for given rain duration t_d). Following rainfall durations had been used for the simulation tests t_d= 10, 20, 30, 45 and 60 minutes. Because of the compact shape of the catchment, simulations examined all four major directions of rainfall movement (E, N, S, W).

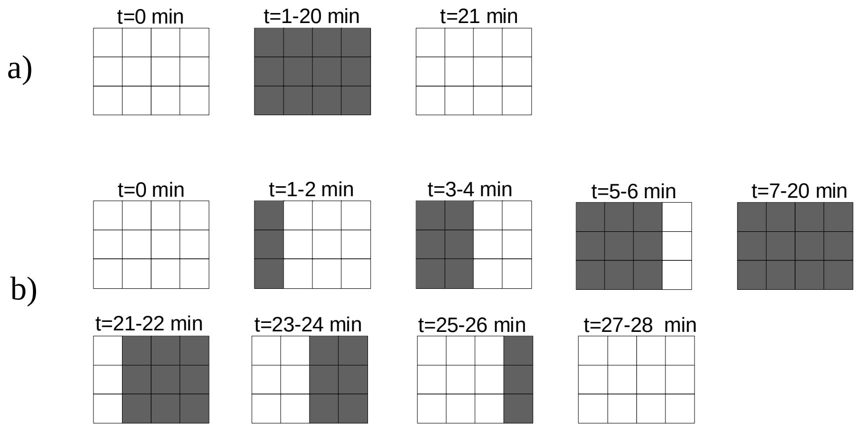

Figure 2. Scheme of rainfall movement over the catchment: a) static rainfall (vop=∞), b) rainfall moving in east direction at speed of 5 m/s

RESULTS OF SIMULATIONS

Maximum flow-rates

Based on the previously mentioned studies (Niemczynowicz [10], De Lima and Singh [6], Singh [15]) it was expected that the peak flow- rates at the outlet will be obtained for the direction of rainfall movement consistent with the general direction of stormwater flow in conduits. This was confirmed in results of the simulations as the largest flow-ratse in the outlet section was recorded for rainfall td=20 min at speed of the 2 m/s in East direction. The flow rate is about 12% (1.27 m^3/s) higher than the intensity obtained for static conditions ($v_r = \propto$). For comparison, the values obtained for the opposite directions of rainfall movement (e.g. E and W or N and S), the differences in the maximum values depend on the flow velocity and was in range: 4÷16.5 % for v_r = 10 m/s and in the range of 21 ÷ 73 % for the v_r = 2 m/s. For example, a 10-minute rainfall moving in south direction (velocity v_r = 2 m/s) results in an Q_{max}= 10.7 m^3/s while the 30-minute rainfall moving in west with analogous velocity results in a flow-rate of 2.35 m^3/s smaller. Meanwhile, in the case of the static conditions rainfall of duration t_d=30 min causes the maximum flow-rates greater by 1.7 m^3/s than for rainfall of duration t_d=10 min.

Table. 1. Maximum flow-rates [m^3/s] In outlet cross-section for static and dynamic variants of rainfalls.

v_r [m/s]	Rain duration							
	10min		20min		30min		45min	
∞	9.06		10.92		10.76		9.18	
	Direction of rainfall movement							
	E	W	E	W	E	W	E	W
2	11.65	6.74	12.18	7.74	11.15	8.34	9.23	8.50
5	10.84	7.73	11.92	9.37	11.10	9.71	9.22	9.05
10	9.68	8.31	11.30	10.23	10.93	10.33	9.21	9.13
	S	N	S	N	S	N	S	N
2	10.69	6.91	11.62	8.41	10.93	9.05	9.17	8.34
5	9.55	8.13	11.55	10.02	10.94	9.96	9.20	9.11
10	9.07	8.54	11.16	10.50	10.87	10.46	9.19	9.16

Comparing these values. it is obvious that define the duration and the intensity is not sufficient to determine "design storm" for the dimensioning of drainage devices.

Simulation results for maximum flow-rates for different directions of rainfall movement were an indication that for sizing of storage reservoirs this influence should be larger. Figure 3a presents sample hydrographs for rainfall of duration t_d=20min as result of rain cell moving over the catchment with velocity of 2m/s in four directions (and also static variant). The comparison shows how significant is the impact of the direction of rainfall moving on the shape of the hydrograph. Hydrographs obtained for the direction E and S are very different shape and maximum values than hydrographs for directions N and W. Figure 3b shows sample influence of the rainfall movement velocity on the hydrograph shape - in most cases this influence is less than impact of movement direction.

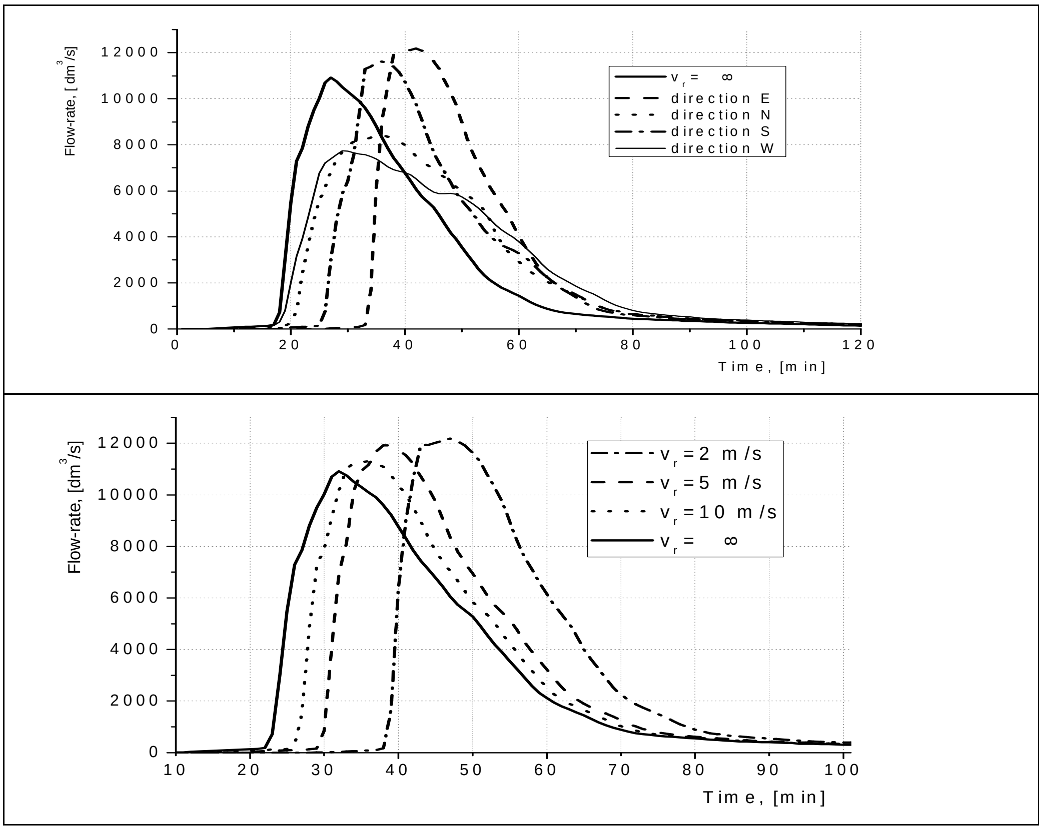

Figure 3a. Hydrographs for rainfall of duration t_d=20min (v_r=2 m/s) for various directions of movement. Fig. 3b. Hydrographs for rainfall of duration t_d=20min (direction E) for various velocities.

Analyzing the shape of the hydrographs its obvious that rainfall movement is an important parameter while required volume is estimated. The influence is directly related to outflow-rate (Q_0). thus simulations were performed for following unit outflow-rates from the storage tank (q_0): 12.5 $dm^3/s{\cdot}ha$. 25 $dm^3/s{\cdot}ha$. 37.5 $dm^3/s{\cdot}ha$ and 50 $dm^3/s{\cdot}ha$. Modeled storage tank is equipped with a side weir (discharge to storage chamber) and a flow regulator to fix quasi-constant outflow rate.

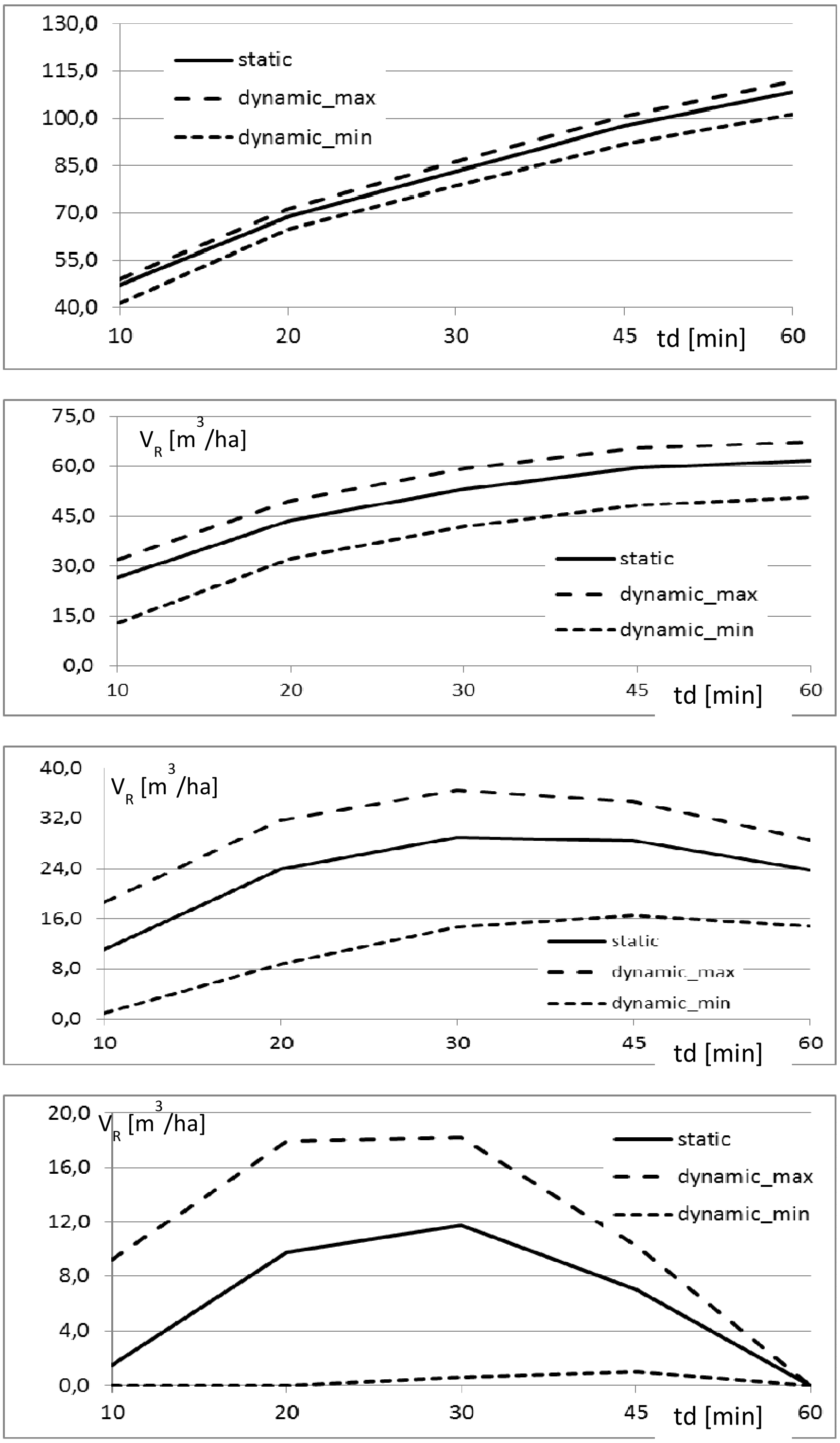

Figure 5. Zestawienie jednostkowych objętości retencyjnych dla warunków statycznych oraz dynamicznych (maximum i minimum): a) Q_0=12.5 dm^3/sha. b) Q_0=25 dm^3/sha. c) Q_0=37.5 dm^3/sha. d) Q_0=50 dm^3/sha.

Figure 5 shows the unit volume of stored stormwater obtained using static as well as dynamic rainfall data for variable value of outflow-rate Q_0. For the dynamic conditions only minimum and maximum values were marked. In all the analyzed cases. the maximum value of V_R has been obtained for variant precipitation moving in E direction at velocity v_r=2 m/s. These volumes were larger than average stored volume obtained in static variant by 700÷1100m^3 depending on the rain duration t_d. In relative terms. this means potentially underestimating the required retention capacity by:

- 3.1 % for q_0=12.5 dm^3/s·ha
- 9.5 % for q_0=25 dm^3/s·ha
- 26.0 % for q_0=37.5 dm^3/s·ha
- 55.5 % for q_0=50.0 dm^3/s·ha

Considering minimum values of V_R obtained for dynamic conditions. the differences are clearly larger and in all cases were obtained for rainfall movement in N direction at velocity v_r=2 m/s.
It should be noted that the relative increase in maximum flow rates (showed in Table 1) usually does not translate into direct growth of investment costs. because it does not necessarily result in a change to a larger diameter of a conduit. When dimensioning storage tanks this relation is simplified - increase of required retention volume usually results in proportional increase of investment costs.
Results presented in this article are recommendations when the dynamic properties of rainfalls should be considered in calculations aimed to estimation of storage capacity. Following factors influence on the results: size of the catchment area (for small areas the dynamic properties of rainfall can be negligible). configuration of the drainage system (average slopes. shape of a catchment etc.) and also local climatic conditions.

SUMMARY

The purpose of the current study was to determine the dynamic properties of rainfall on estimation of required storage capacity of storage tanks. The following conclusions can be drawn from the present study:

- the maximum peak flow-rates for the dynamic conditions can be larger to a few percent to 30% (depending on the t_d and v_r) higher than for the stationary variant (no movement).
- influence of the direction and speed of rainfall movement on the shape of inflow hydrograph to the reservoir is significant. which has a direct impact on the calculated volume of stored stormwaters.
- the impact of the movement of precipitation on stored volume is closely related to outflow rate from retention reservoir (i.e. for q_0=12.5 dm^3/sha the difference between static and dynamic variants is less than 10% while for q_0=50 m^3/sha it reach over 90%).
- the maximum volume of stored stormwaters occurs with rainfalls whose velocities are close to flow velocity in the conduits (2 m/s) and parallel to general direction of flow in the drainage system.
- relative differences in obtained results between static and dynamic ranged from 3% to 55% depending on q_0. In absolute terms it about 700 ÷ 1100m^3. and expressed as unit volume: 6.5 ÷ 8.0 m^3/ha of impervious area.

REFERENCES

[1] Bell V. A. and Moore R. J., “The sensitivity of catchment runoff models to rainfall data at different spatial scales”, *Hydrol. Earth Syst. Sci*, 4, (2000), pp 653–667.

[2] Berne A., Delrieu G., Creutin J. D., and Obled C., “Temporal and spatial resolution of rainfall measurements required for urban hydrology”, *J Hydrol.*, 299(3–4), (2004), pp 166–179.

[3] Borga M., Anagnostou E. N., Bloschl G., and Creutin J. D., “Flash Floods: observations and analysis of hydrometeorological controls”, *J. Hydrol.*, (2010), 394(1–2), pp 1–3.

[4] Burszta-Adamiak E. and Mrowiec M., “Modelling of green roofs' hydrologic performance using EPA's SWMM”, *Water Science and Technology*, vol. 68, (2013), pp 36-42.

[5] Clemens F., “Hydrodynamic models in urban drainage: Application and calibration, doctoral dissertation”, TU Delft, Delft University Press, (2001).

[6] De Lima J. L. and Singh V. P., “The influence of the pattern of moving rainstorms on overland flow”, *Adv. Water. Res*, 25(7), (2002), pp 817–828(12).

[7] Krajewski W. F. and Smith J. A., “Radar hydrology-rainfall estimation”, *Adv. Water Resources*, 25, (2002), pp 1387–1394.

[8] Morin E., Goodrich D. C., Maddox R. A., Gao X. G., Gupta H. V. and Sorooshian, S., “Spatial patterns in thunderstorm rainfall events and their coupling with watershed hydrological response”, *Adv. Water Res.*, 29, (2006), pp 843–860.

[9] Naden P. S., “Spatial variability in flood estimation for large catchments: the exploitation of channel network structure”, *Hydrol. Sci. J.*, 37, (1992), pp 53–71.

[10] Niemczynowicz J. and Bengtsson L., “What practitioners need from theoreticians?” *Atmospheric Research*, 42, (1996), pp 5-17.

[11] Niemczynowicz J., “Investigation of the influence of rainfall movement on runoff hydrograph: Part I. Simulation of conceptual catchment”, *Nordic Hydrology*, 15, (1984), pp 57–70.

[12] Obled C., Wendling J. and Beven, K., “Sensitivity of hydrological models to spatial rainfall patterns: An evaluation using observed data”, *J. Hydrol.*, 159, (1994), pp 305–333.

[13] Rodriguez-Iturbe I., Marani M., D’Odorico P. and Rinaldo, A., “On space-time scaling of cumulated rainfall fields”, *Water Resour. Res.*, 34, (1998), pp 3461–3469.

[14] Schilling W., “Rainfall data for urban hydrology: what do we need?”, *Atmospheric Resources*, vol. 27, (1991), pp 5-21.

[15] Singh V. P., “Effect of the direction of storm movement on planar flow”, *Hydrol. Process.*, 12, (1998), pp 147–170.

[16] Smith M., Koren V., Zhang Z., Reed S., Pan J. and Moreda F., “Runoff response to spatial variability in precipitation: an analysis of observed data”, *J. Hydrol.*, 298, (2004), pp 267–286.

[17] Vaes G., Willems P. and Berlamont J., “Areal rainfall correction coefficients for small urban catchments”, *Atmospheric Research*, 77, 2005, pp 48– 59.

[18] Zoccatelli D., Borga, M., Zanon, F., Antonescu, B. and Stancalie, G., “Which rainfall spatial information for flash flood response modelling?, A numerical investigation based on data from the Carpathian range, Romania”, *J. Hydrol.*, 394(1–2), (2010), pp 148–161.