1 **Usage of the WRF/DHSVM model chain for simulation of extreme floods in mountainous areas: a**

2 **pilot study for the Uzh River Basin in the Ukrainian Carpathians**

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7

8 **Abstract**

9 The mesoscale meteorological/distributed hydrological model chain WRF/DHSVM was calibrated for simulation of extreme

10 flood events in Uzh River basin in Ukrainian Carpathians. The flood event which happened in July, 2008 was successfully

11 reproduced by using final analysis meteorological input data of the US National Centers for Environmental Prediction (NCEP).

12 For climate run for the period of 1960-1990 the NCEP Reanalysis-1 meteorological data were used. Frequencies of extreme

13 precipitation events obtained by fitting of the measured and simulated precipitation time series with the Generalized Extreme

14 Value (GEV) distribution were very close. Simulated water discharges for the very extreme floods happening from once per 50

15 to once per 100 years were in good agreement with the water discharges of the same frequencies obtained by statistical

16 processing of measurements.

17 **Keywords:** high precipitation events, water discharge, mesoscale meteorological model, distributed hydrological model,

18 statistical modeling, GEV distribution.

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1. **Introduction**

Assessment of the consequences of the global climate change on the occurrence of hazardous weather events such as floods in specific regions require usage of downscaling procedures (e.g. Maraun et al. 2009) with respect to the data representing climate change projections of the general circulation models (GCMs). GCMs data are typically available with low spatial resolution of about 1 degree. Dynamical downscaling is physically based method in which regional climate models (RCMs) are used for calculation of meteorological fields on fine-scale grids with resolution from 30 km down to about 1 km. Modern mesoscale meteorological models such as WRF (Skamarock et al. 2008) are capable of taking into account the influence of terrain on atmospheric flow. For instance they can produce realistic precipitation patterns in mountainous terrain including precipitation fields formed by meso-β scale convective systems (Fiori et al. 2014). Therefore such models often used as RCMs. Assessment of vulnerability of the particular region with respect to floods requires also calculation of the water discharges in rivers of interest which could be performed with the distributed hydrological models such as DHSVM (Wigmosta et al. 2012), TOPKAPI (Todini and Ciarapica 2002), DELTA/HYDRO (Mita and Catsaros 2012) and other. Hydrological models use precipitation and other meteorological fields calculated by the RCMs.

The model chains of the mesoscale meteorological-distributed hydrological models are often used in climate studies of large water catchments (e.g. Huziy et al. 2012). For small water catchments of mountain rivers such model chains are usually used in context of short-term operational flood hazards forecasting (e.g. Davolio et al. 2013). Usage of such model chains in climate studies had rarely been performed because for small catchments the results of the simulated water discharges become very sensitive to the output of the RCMs: small spatial shifts of the precipitation fields in simulations can lead to significant change in the results of hydrological models. Thus in long climate runs of the meteorological/hydrological model chains applied to small mountainous rivers using reanalysis data such as NCEP Reanalysis data set (Kalnay et al. 1996) individual flood events may be not reproduced. From the other hand the statistical properties of the floods events such as their frequency and return periods may be still well reproduced in climate runs of meteorological/hydrological model chains.

The aim of the present work is to test the capability of the WRF/DHSVM model chain to reproduce the statistics of extreme flood events on mountainous rivers, such as the Uzh River in Ukrainian Carpathians. The present study is restricted by heavy flash floods happening during warm season due to limited amount of data available to authors for model calibration. In the following chapters we describe the site being under study (section 2); then we describe the WRF and DHSVM model settings (section 3). In section 4 we present the results of comparisons of the simulated results with measurements taken during flood event which happened in the region of interest in July, 2008. In section 5 we simulate statistics of extreme precipitation and extreme flooding events during the period of 'reference climate' of 1960-1990 and compare simulated results with measurements. The results are summarized in the conclusions sections.

2. **Study area**

1 Carpathian region is one of the most flood vulnerable areas in Ukraine (Fig. 1). There was a series of catastrophic floods in that

2 region within the last decade; the most hazardous being in the years 1998 and 2001 in the Tisza River Basin - Zakarpatska

3 Oblast - western watersheds of Carpathian mountains, and in July 2008 in the Dniester and upper Prut Basins (eastern

4 watersheds of Carpathian mountains). The precipitation events occurring in the Ukrainian part of the Carpathian mountains are

5 known to contribute significantly to flood occurrences in Danube and Dniester river basins.

6 The test case of this study is the Ukrainian part of the Uzh River watershed with the outflow crossection in city

7 Uzhgorod at the Ukrainian – Slovakian Border (Fig. 1). Watershed is known for snowmelt flood and rain flash floods that

8 occur 3-8 times per year. Most of the extreme precipitation events during flash floods in this region last for 2-5 days and more

9 (Krasnova 2002). Hence watershed is included in the list of the most impacted by high floods river basins of Ukraine. Uzh

10 River is a tributary of the Laborets river. It flows along the Tysa Lowland, through the Transcarpathian region of Ukraine.

11 Length of the Ukrainian part of the Uzh River is 112.8 km while area of the Ukrainian part of the watershed is 1970 km2.

12 Maximum elevation in the study area is 1475 m, minimum elevation is 98m. There are six hydrometeorological gauging

13 stations within the area of study where measurements took place for more than 10 years. All stations measure precipitation,

14 temperature, water discharge and water level. Additionally 2 stations (Velyki Berezny and Uzhgorod) measure wind speed. The

15 time interval of precipitation measurements is normally 24 hours while the time interval of water discharge measurements is

16 usually 12 hours. During floods additional measurements of water discharge and precipitation could be taken on irregular basis.

17 The time interval of measurements of the rest meteorological variables is 3 hours.

18 **3. Model chain**

19 *3.1. Setup of the WRF model*

20 Calculations had been performed with WRF-ARW mesoscale meteorological model (Skamarock et al. 2008). A sequence of 4

21 nested computational domains with spatial resolutions of: 27, 9, 3 and 1 km were used for simulations. All the domains were

22 centered on the same point so that the inner domain having size of 220x180 km fully covered the Ukrainian Carpathians while

23 the outer domain covered region of 1300x1300 km. In vertical direction computational domains were subdivided onto 28

24 vertical levels. The geographical data of the US Geological Survey available at the site of the WRF-ARV model

25 (http://www.mmm.ucar.edu/wrf/users) with spatial resolution of 30 sec. had been used for providing WRF with geographical

26 data. The following set of physical parameterizations had been used (described in Skamarock et al. (2008) and named according

27 to conventions of the same work). The microphysical processes in clouds were accounted for with WSM6 parameterization

28 which describes formation processes of cloud and rain water, ice, snow and graupel. The longwave radiation was calculated

29 with RRTM parameterization, while the shortwave radiation was calculated with Goddard parameterization. The turbulence

30 exchange processes in atmospheric boundary layer were calculated with the MRF parameterization, which take into account

31 non-local nature of turbulence exchange in convective boundary layer. The Kain-Fritsch parameterization had been used for

1 taking into account cumulus clouds. The last option was not applied in the 4-th nested domain since cumulus parameterizations

2 need not to be applied when simulations are performed with spatial resolution of 1 km.

3 *3.2. Modification and setup and of the DHSVM* model

4 Distributed Hydrology Soil Vegetation Model – DHSVM (Wigmosta et al. 2002) - was developed by the Land Surface

5 Hydrology Research Group at the University of Washington and Pacific Northwest National Laboratories, WA (Wigmosta, et

6 al., 1994; Wigmosta and Burges 1997; Wigmosta and Lettenmaier 1999; Wigmosta et al., 2002). Let briefly describe the

7 geospatial data that were used for modeling. Topographical maps were constructed from the digital elevation model (DEM)

8 SRTM DEM v.4 (Jarvis et al., 2008) having 90 m resolution. Soil maps including the US Department's of Agriculture soil

9 taxonomy were obtained from the HWSD – Harmonized World Soil Database (HWSD, 2014, Fischer et al., 2008). Spatial

10 resolution of the HWSD maps is approximately 1 km. Land cover map had been obtained from GlobCover database (Bicheron

11 et al., 2008). The spatial resolution of the land cover data available from GlobCover is about 250 m.

12 For the model implementation for Uzh River the model source code has been downloaded from the web site (DHSVM

13 v.3.0, 2012) and the input GIS data listed above had been processed in accordance with the requirements for the input data of

14 DHSVM. Source code analysis showed that in the original DHSVM v.3.0 the D4 flow direction approach is used (Costa-Cabral

15 and Burges, 1994) for the simulation of surface routing, which as will be shown below in this case leads to a large accumulation

16 of water on the mountain slopes. So, the following method of the D8 approach had been implemented in DHSVM in present

17 work in which kinematic-wave equation describing overland flow is integrated in eight directions (Fig. 2) for a *i*-th cell:

18
$$h_i + \frac{\Delta t}{\Delta x} \sum_{j=1}^{8} Q_{i,j} = \breve{h}_i + \frac{\Delta t}{\Delta x} Q_{in,i} + \Delta t R_{ex} \qquad\qquad (1)$$

19 where Δt is the computational time step; Δx is the cell size; h_i and $\breve{h}_i$ are the water depths in the *i*-th cell at present and

20 previous time levels respectively; $Q_{i,j}$ is the outflow water discharge from *i*-th cell in the *j*-direction; $Q_{in,i}$ is the inflow

21 water discharge into *i*-th cell; R_{ex} is the rainfall excess rate. The water discharge $Q_{i,j}$ is based on a uniform flow equation

22 $Q_{i,j} = S_{0j}^{1/2} \big/ n\, h_i^{5/3}$, where *n* is the Manning roughness coefficient; $S_{0j} = \alpha_j \dfrac{z_9 - z_j}{\Delta x}$ is the slope of land surface in the *j*-

23 direction; α_j equals 1 for cells with even numbers and $1\big/\sqrt{2}$ for cells with odd numbers. We consider overland water flow

24 only for $S_{0j} > 0$. A solution of the equation(1) is obtained by using the Newton-Raphson technique. The implemented D8

25 approach had significant effect on the results of calculations as will be demonstrated below (cf. Fig. 6). Additionally for

26 increasing the robustness of the simulations an implicit finite difference scheme had been implemented for solving the channel

27 flow equation in DHSVM.

28

4. Results

4.1. DHSVM calibration

The model had been calibrated using measurement data collected on site during warm season of 1996. For model calibration the meteorological data collected at the measurement stations described in section 2 had been used as input data. The output data had been compared with hydrological measurements (water discharges) collected at Uzhgorod hydrological station (most of the other hydrological stations were not yet operational in 1996) and maximum infiltration rate parameter of DHSVM had been adjusted. The obtained results showed satisfactory agreements with measurements during the calibration period as this is confirmed by Fig. 3 and the statistical indicators of model error – Nash-Sutcliffe efficiency

$$NSE = 1 - \left\langle \left(Q_o - Q_m \right)^2 \right\rangle \Big/ \left\langle \left(Q_o - \left\langle Q_o \right\rangle \right)^2 \right\rangle \text{ and percent bias } PBIAS = 100 \cdot \left\langle Q_o - Q_m \right\rangle \Big/ \left\langle Q_o \right\rangle \text{ (Moriasi et al, 2007)}$$

which are presented in Table 1. In the above formulas $\left\langle \; \right\rangle$ - is averaging operator, Q is the parameter of interest (water discharge), indices 'o' and 'm' stay for observed and simulated values respectively.

4.2. Simulation of flood in July, 2008 by WRF/DHSVM model chain

During 21-27 July, 2008 the territory of Western Ukraine was influenced by catastrophic floods which caused great damage in six regions of Ukraine. This catastrophic flood was caused by the intensive cyclonic activity on the territory of Central Europe during this period and by interaction of the cold and warm air masses on the territory of Western Ukraine. This caused intense thunderstorms and convective precipitation, which were further enhanced by the influence of the Carpathian mountains. The detailed description of synoptic conditions which caused the mentioned floods is described by Pirnach et al. (2010).

The flood on the Uzh River was not so great as on the neighbor rivers in the Transcarpathian Region. However precipitation and corresponding increase in water discharges were also quite large and approximately corresponded to 5-year flood. During the considered period the time interval of precipitation measurements was 24-hours and the corresponding measurements are shown on Fig. 4. The maximum precipitation at all stations was observed during the 25-th July, 2008 and accumulated precipitation on that day varied from 25 to 45 mm. Simulations with WRF were performed by a sequence of 54-h runs starting from the 1st of July, 2008 and using final analysis data (FNL) of the US National Center for Environmental Prediction (NCEP, 2000). The runs had been reinitialized each 48 hours so that overlap between runs had been set to 6 hours and the calculated meteorological fields for DHSVM (2-m temperature and humidity, 10-m wind speed, shortwave and longwave radiation, precipitation, temperature lapse rate) were saved and passed to DHSVM each 3 hours. The starting date had been selected early enough to provide the hydrological model with the necessary meteorological data during the spin-up period. The comparison of the simulated daily precipitation with measurements is shown at Fig. 4. As it is seen from the figure at all stations maximum precipitations which occurred during July, 25-th are well reproduced. WRF largely underestimates precipitation which occurred on July, 27-th. As a result of this WRF underpredicts the averaged over all stations accumulated precipitation during the period of July, 21-27th as compared to measurements (PBIAS=22% as presented in Table 1).

1 Nevertheless the correlation between the calculated and measured results is quite high: 89% and NSE=0.5 (Table 1) which also

2 indicates that the overall the agreement between the calculated and measured precipitations is good.

3   Comparison between observed at three measurement stations and simulated hydrographs obtained by modified

4 DHSVM with taking into account infiltration and interception is shown in Fig. 5. For all three stations model well predicts the

5 magnitudes of the peak discharges. However the simulated peak discharges occur somewhat earlier as compared to

6 measurements. Additionally the water discharges prior to main peak are underestimated in simulations. Therefore the value of

7 the NSE is quite low (NSE=0.22). Shifting of the simulated hydrogtaphs in time by 12 hours results in much better NSE=0.5.

8 The above results demonstrate the need for more frequent precipitation and water discharge measurements in this region at least

9 during flood periods and additional model evaluation with respect to the more detailed measured time series.

10   Fig. 6 shows the effect of the newly implemented D8 approach in DHSVM described above on the results of

11 simulations of the July 2008 flood. As it is seen from the figure D4 approach originally implemented in DHSVM lead to large

12 water accumulation on the watershed and to underestimation of the peak water discharge by the factor of 2.5 even when

13 infiltration, evapotranspiration and interception were not taken into account. With the D8 approach the water accumulation is

14 greatly reduced and the simulated peak water discharge is overestimated as expected due to neglect of infiltration,

15 evapotranspiration and interception. By taking into account those processes in the modified DHSVM the results of simulations

16 become in good agreement with observations as described above.

17 *4.3. Simulation of the statistics of extreme precipitation and flooding events for the period 1960-1990*

18 In climate runs for the period of 1960-1990 we used NCEP reanalysis data (Kalnay et al. 1996) which cover the long enough

19 period and they are freely available from the NOMADS servers (Rutledge et al., 2006). In this part of work the aim was to

20 study the ability of model chain in reproducing climate statistics of extreme precipitations and floods rather than reproducing

21 individual high flood events in Uzh River basin. Since the present research had been restricted by flash-floods happening during

22 warm season in all the data processing procedures described below we excluded the days from December, 1st to April, 30th.

23   Simulations had been performed in the computational domain described in previous section. Simulations for the whole

24 period of 1960-1990 using WRF with 1 km grid resolution appeared to be unfeasible because of computational purposes. On

25 the available computational resources (a computational cluster with 40 cores 2.0 GHz) calculations could last a few years. To

26 overcome this difficulty we identified the time intervals with high precipitation amounts which were simulated using WRF.

27 Those time intervals were selected using the following approach. The measured precipitation data had been processed for the

28 period of 1960-1990 and the days with daily precipitations exceeding 20 mm in the area of study had been identified. If such

29 days were close to each other (i.e. if they were separated in time by no more than 2 weeks), they fell into the same simulation

30 interval. Additionally 2 days had been added to the beginning and to the end of each simulation interval. In total 128 time

31 intervals had been identified for simulations which covered 1329 days.

1   Precipitation measurements for the period of interest are available from the web page of the European Climate

2   Assessment & Dataset project (ECA&D, 2014). Daily precipitation data are available only for 2 stations located inside the Uzh

3   River Basin: Uzhgorod and Velyki Berezny. Thus the Uzh River Basin averaged precipitation could be roughly represented by

4   the average over these 2 stations (hereafter refereed as basin-averaged precipitation). The time series of the daily basin-

5   averaged precipitations had been processed and the frequencies of exceedance (FE, [1/year]) of different threshold values had

6   been calculated (shown in Fig. 7 by cross-signs).

7   For the statistical modeling of the probability distribution function (PDF) of daily precipitation we used the

8   Generalized Extreme Value (GEV) distribution (e.g. Wilks, 2006) since this distribution is typically frequently used for

9   analyzing statistics of rare events, i.e. such that happen once per few years (Wilks, 2006, Klein Tank et al., 2009). GEV

10   distribution is usually applied to time series of annual maximums of the observed quantity (the so-called block-maximum

11   method, Klein Tank et al., 2009). Thus the time series of annual maximums of basin-averaged precipitations had been fitted

12   with GEV distribution by using the MATLAB gevfit function.

13   The corresponding complementary cumulative distribution function (CCDF) of the basin-averaged precipitation had

14   been also calculated from the PDF:

$$CCDF(x) = 1 - CDF(x) = P(X > x).\qquad(1)$$

16   In the above relationship CDF(x) is cumulative distribution function, P is the probability of daily precipitation amount X to

17   exceed the threshold value x. This probability could be easily compared to the mentioned above frequency of exceedance by

18   multiplying CCDF on a number of days in 1 year. FE corresponding to CCDF obtained by fitting measurements with GEV

19   distributions is also shown at Fig. 7. The results of calculations had been processed in similar way. Comparison of the

20   exceedance frequencies obtained by the described above processing of measurements and results of calculations shown at Fig. 7

21   is good.

22   Simulations of water discharges in Uzh River with DHSVM had been performed using the meteorological fields

23   calculated by WRF and listed above in section 4.2. The time interval between outputs of the meteorological fields to be used by

24   DHSVM had been set equal to 3 hours. The same as for precipitation the time series of the simulated and measured daily-

25   averaged water discharges in Uzhgorod had been processed and the corresponding frequencies of exceedance of different

26   threshold values had been calculated (shown in Fig. 8 by signs). As far as extreme floods are considered with return periods of

27   more than 1 year the fitting of PDF is typically based on time series of annual maximum water discharges (Klein Tank et al.,

28   2009). Apart from resolving the issue of decorrelation of the time series, such approach allows to avoid the influence of the

29   relatively small water discharges on the results of fitting. From the other hand such approach greatly decreases number of

30   processed records which is undesirable in statistical analysis. Therefore in present work while counting exceedance frequencies

31   of a given threshold value of water discharge only those records were counted which were separated in time by more than 3

32   months.

1   Statistical modeling of the PDF of daily-averaged water discharges in Uzhgorod had been performed by using the

2 same method as was applied above to precipitation time series. The corresponding CCDFs obtained by fitting measuremes and

3 calculated time series of daily-averaged water discharges with GEV distributions are also shown at Fig. 8. Contrary to

4 measurements of daily averaged water discharges which were available to authors on a daily basis, the maximum measured

5 water discharges had been available on a yearly basis. Therefore GEV-fitting of measured and simulated maximum water

6 discharges had been also performed and the corresponding results are presented in Table 2.

7   As it follows from the results presented in Fig. 8 and in Table 2, the agreement between the CCDFs obtained by

8 statistical processing of measured and simulated water discharges is satisfactory. The disagreement is greater for higher

9 frequencies (smaller return periods) which may be caused by the fact that only time periods with large daily precipitation were

10 selected for simulations for the computational reasons (cf. above). Therefore the water discharges corresponding to return

11 periods of about 10-25 years are underestimated in simulations. However the frequencies of most extreme water discharges

12 with the return periods of 50-100 years agree well.

13 **5. Conclusions**

14 In present work we studied the perspectives of the usage of the mesoscale meteorological/distributed hydrological model chain

15 WRF/DHSVM for assessments of extreme flood events in small mountainous watersheds. The watershed of the Uzh River in

16 Transcarpathian Region of Ukraine had been used as a test site. Simulations of the flood event which happened in July, 2008

17 showed that the model chain is capable of reproducing individual flood events provided that accurate enough input

18 meteorological data such as NCEP final analysis data are available. Simulations for the climate of 1960-1990 were performed

19 using NCEP Reanalysis-1 data. Instead of simulating the whole 30-years period only the time intervals with large enough daily

20 precipitation were selected for simulations. The results of simulations together with the available precipitation and water

21 discharge measurements had been fitted with GEV distribution to establish the statistical properties of extreme precipitation and

22 extreme flood events happening from 1/10 to 1/100 years. Frequencies of extreme precipitation events obtained by GEV-fitting

23 of the measured and simulated precipitation time series appeared to be very close. The simulated water discharges appeared to

24 be underestimated for moderately extreme floods happening from once per 10 to once per 20 years. However simulated water

25 discharges for the very extreme floods happening from once per 50 to once per 100 years were in good agreement with the

26 water discharges obtained by statistical processing of measurements. Further work is necessary to extend the results of present

27 study to snowmelt flash floods.

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2 **Tables**

3 Table 1. Nash-Sutcliffe efficiencies and percentage biases of the calculated results

Model	Stat. Indicator [Units]	Description	Value
DHSVM	PBIAS [%]	Calibration period May-Oct. 1996	9
DHSVM	NSE (peak discharges)	Calibration period May-Oct. 1996	0.34
WRF	PBIAS [%]	Flood period, July, 2008	22
WRF	NSE	Flood period, July, 2008	0.5
DHSVM	PBIAS [%]	Flood period, July, 2008	36
DHSVM	NSE	Flood period, July, 2008	0.22
DHSVM	NSE	Flood period, July, 2008, simulated results shifted in time by +12 h	0.5

4

5 Table 2. Water discharges for different exceedance frequencies (return periods) obtained by GEV-fitting the results of

6 measurements and calculations of the WRF/DHSVM model chain

Exceedance frequency, 1/years	Return period, years	Maximum daily discharge, m^3/s		Daily average discharge, m^3/s	
		GEV fitted measurements	GEV fitted results of calculations	GEV fitted measurements	GEV fitted results of calculations
0.1	10	655	411	403	303
0.04	25	848	637	518	470
0.02	50	1005	865	611	638
0.01	100	1173	1161	709	853

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2 **Figure captions**
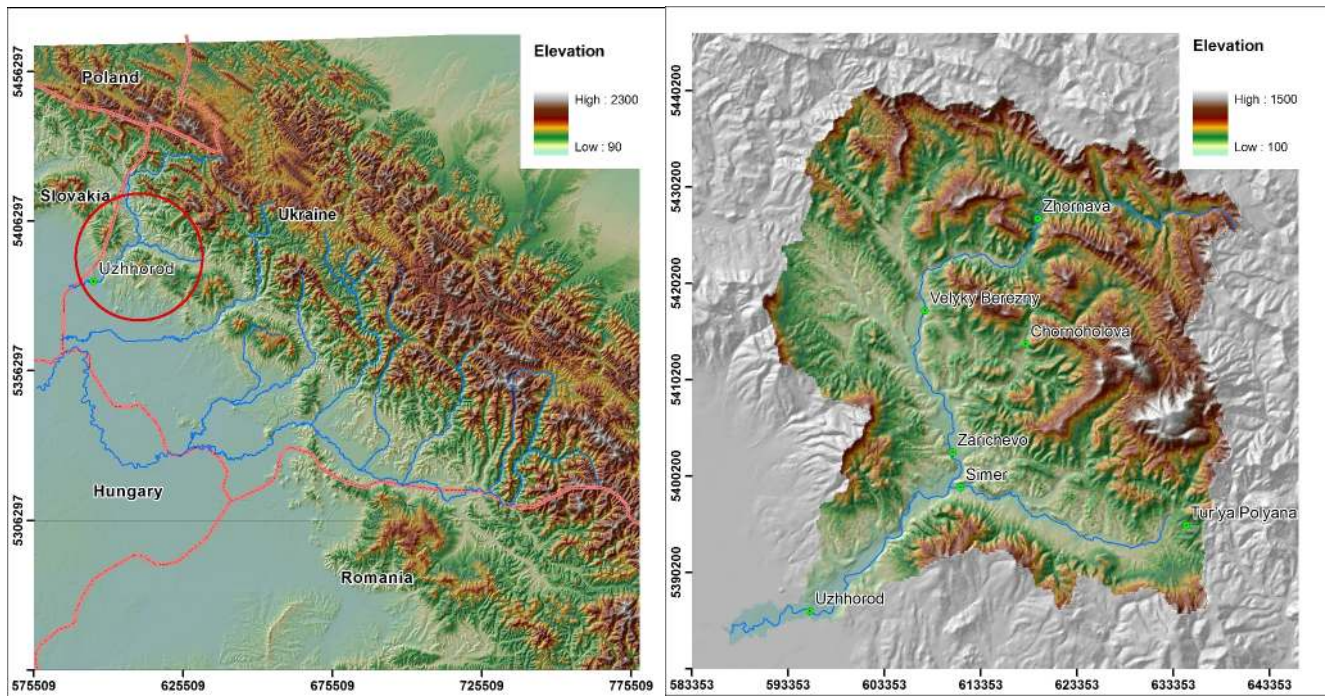
3

4 Fig.1 Carpathian mountains and Uzh river watershed in Ukraine (upper); Uzh River river network and the the locations of

5 hydrometeorological stations overlaid on the topography of the watershed (bottom); coordinates are in UTM, 34N zone
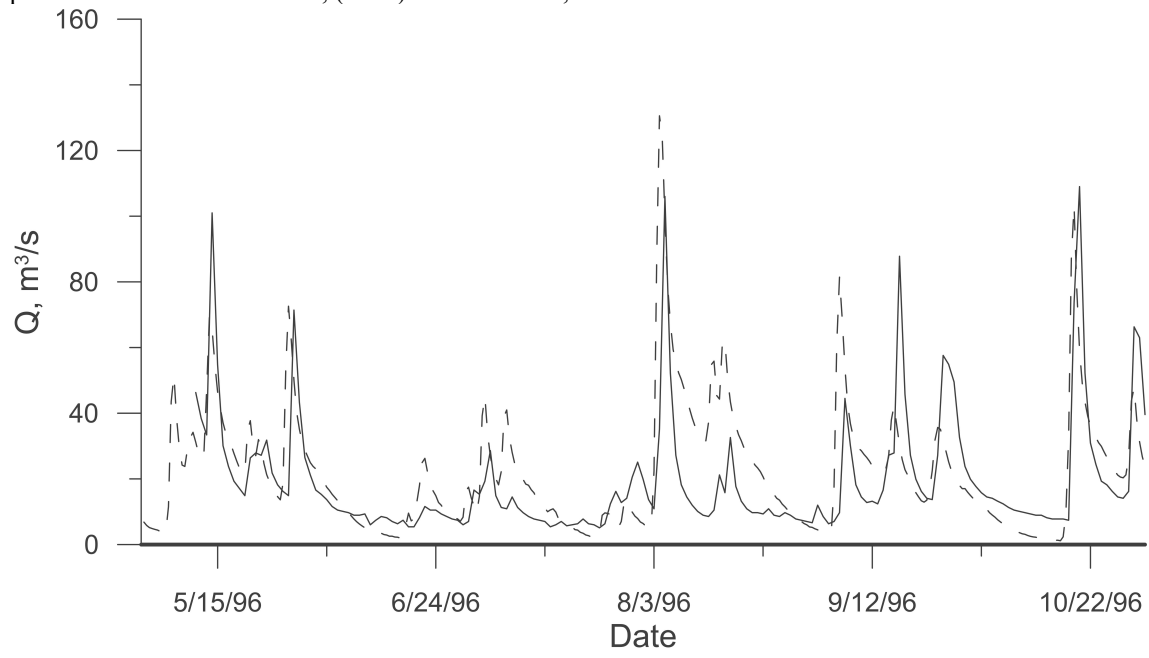
6
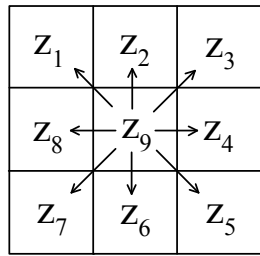
7

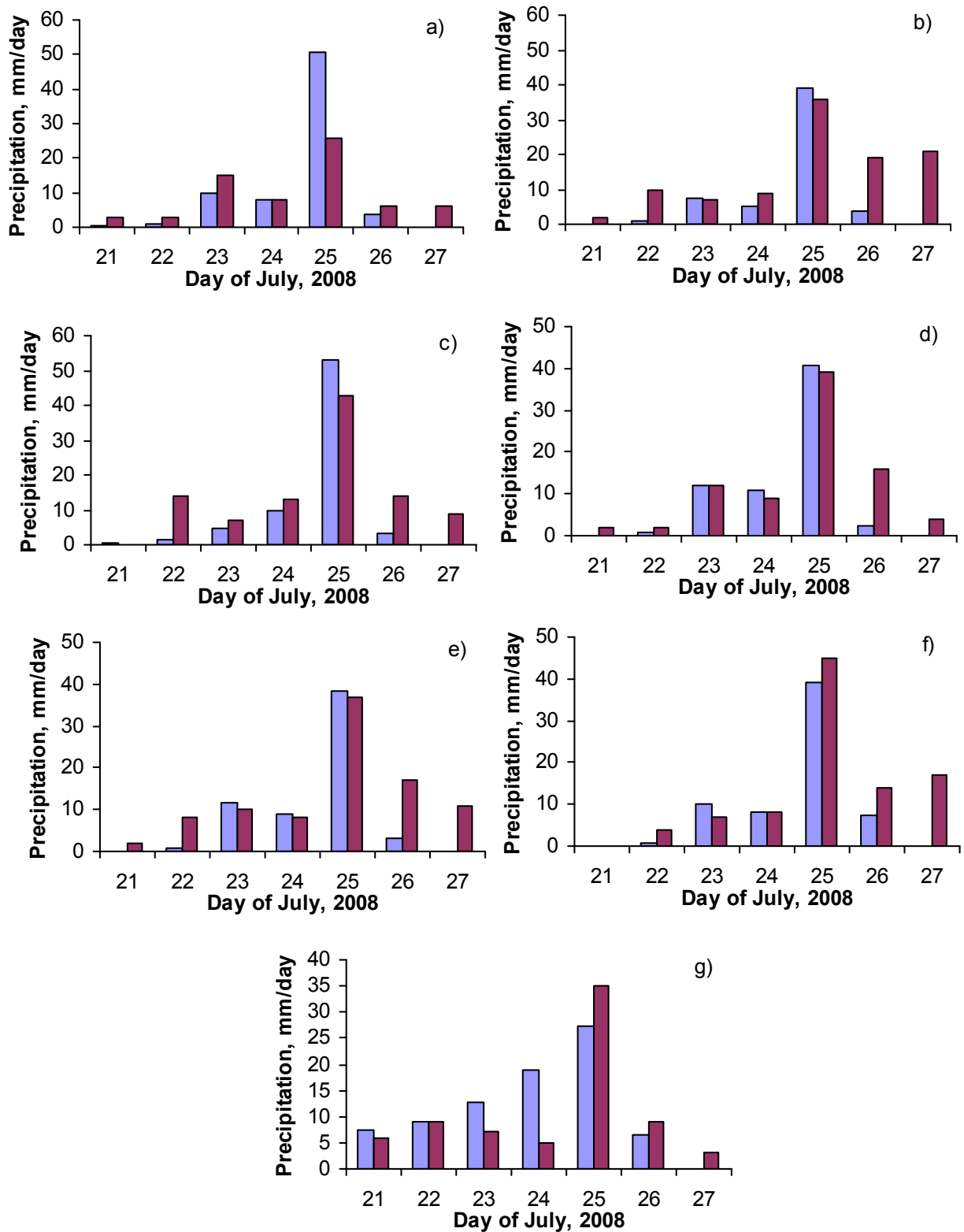8 Fig. 2. Flow directions in D8 flow-routing algorithm

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2   Fig. 3 Observed (solid line) and simulated by DHSVM (dashed line) water discharges during calibration period
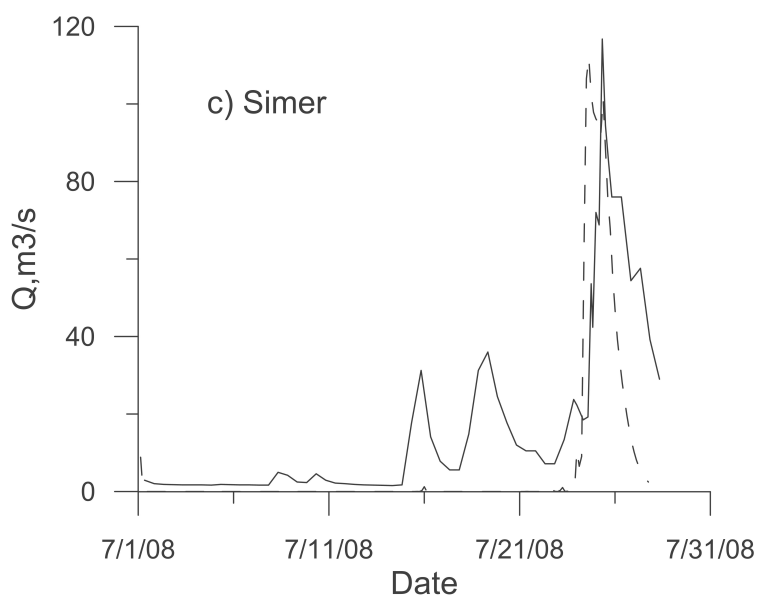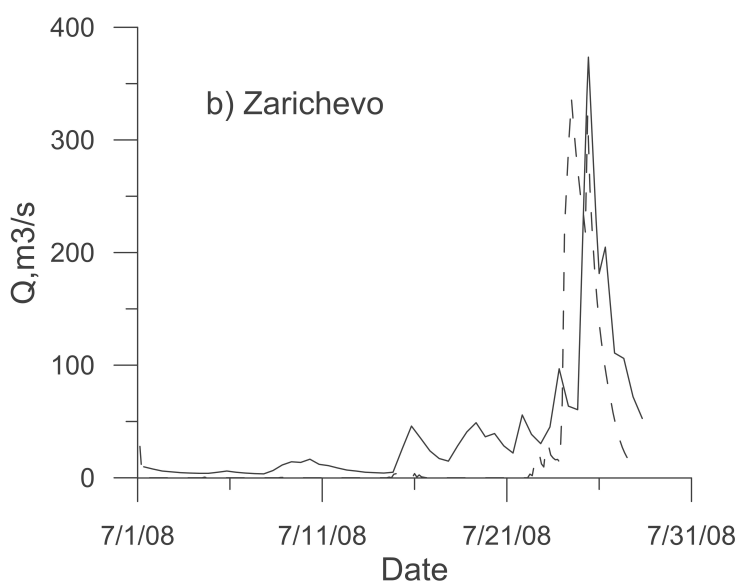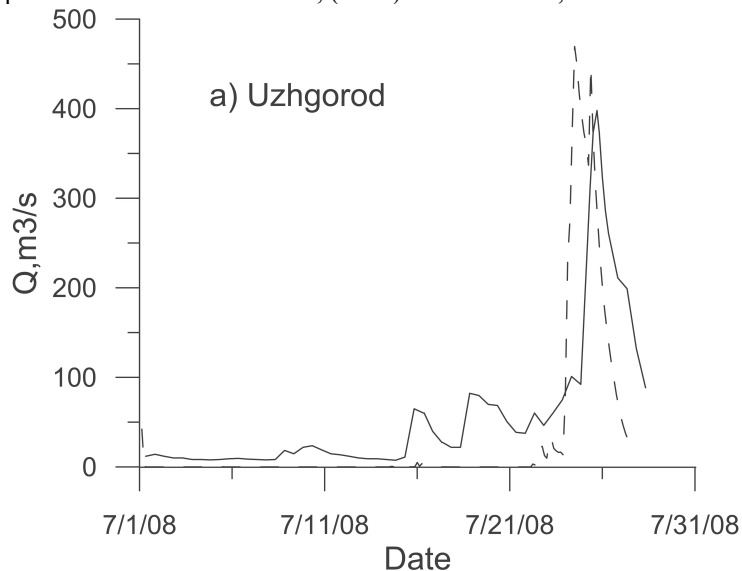
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Fig. 4 Measured (violet) and simulated by WRF (blue) daily precipitations during flood of 21-27 July 2008 at measurement

stations: a) Uzhgorod; b) Chornoholova; c) Zhornava; d) Simer; e) Zarichovo; f) Turia Poliana; g) Velyki Berezny

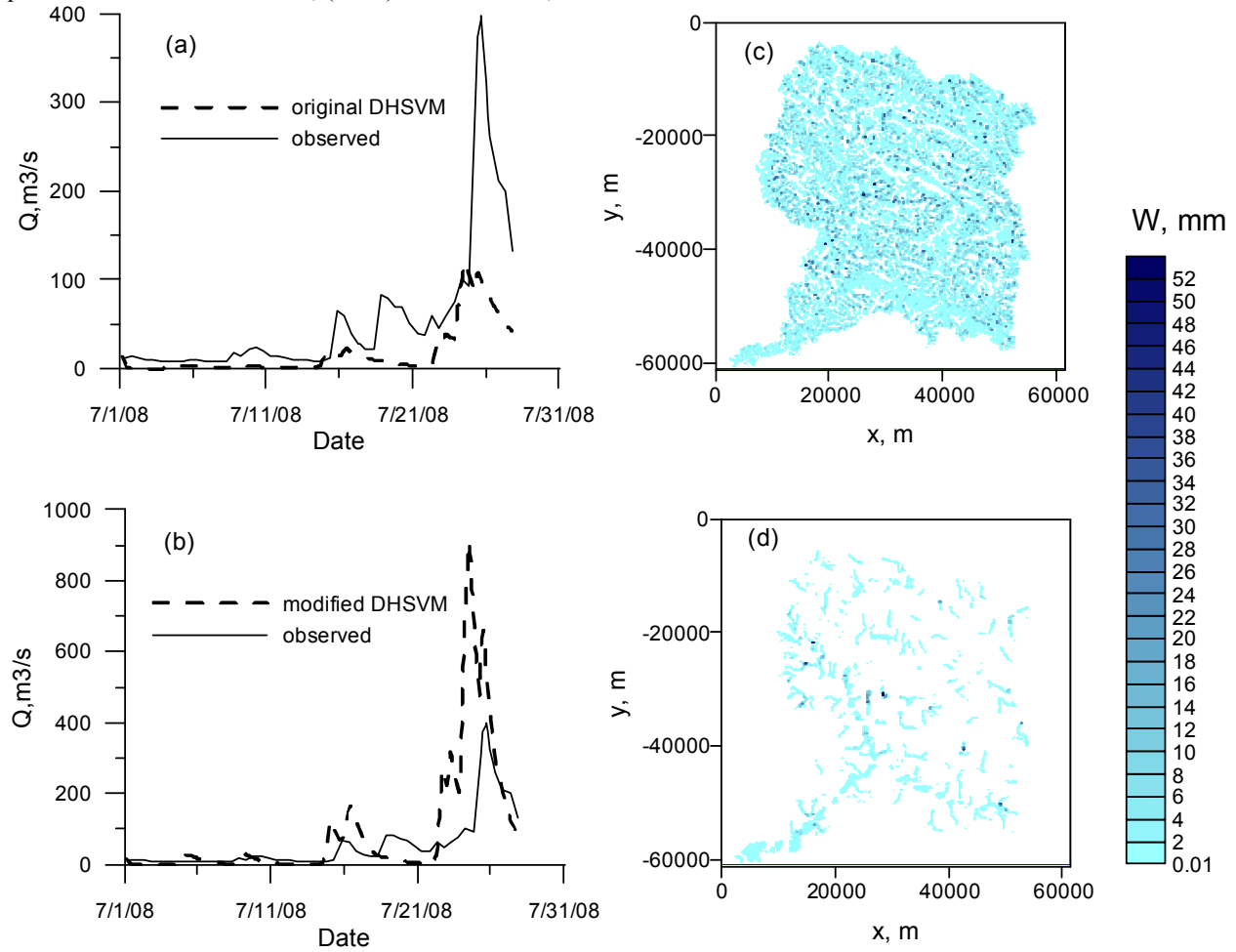Fig. 5 Comparison between observed (solid line) and simulated (dashed line) with DHSVM water discharges at Uzhgorod, Simer and Zarichevo stations during flood in July, 2008

Fig. 6. (a) Simulated hydrograph in Uzhgorod obtained for the conditions of July, 2008, by using original DHSVM v.3.0 without taking into account infiltration, evapotranspiration and interception, (b) Amount of water remained in simulations of original DHSVM v 3.0 on the mountain watershed, (c) the same as (a), but calculated with the modified DHSVM and (d) the same as (b) but calculated with the modified DHSVM.
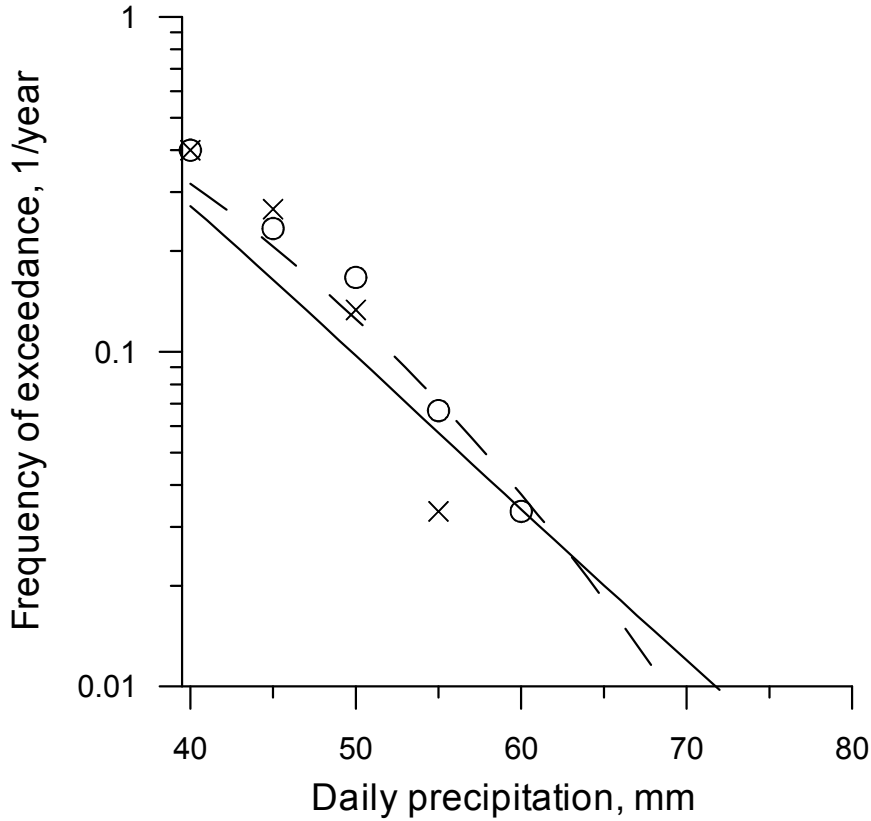
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2 Fig. 7 Exceedance frequency of extreme precipitation averaged over stations located in Uzh River basin (Uzhgorod and Velyki

3 Berezny) for the period of 1960-1990; '×' – results of measurements; black line corresponds to CCDF obtained by fitting

4 measurements with GEV distribution; 'o' – results of calculations; dashed line corresponds to CCDF obtained by fitting the

5 results of calculations with GEV distribution
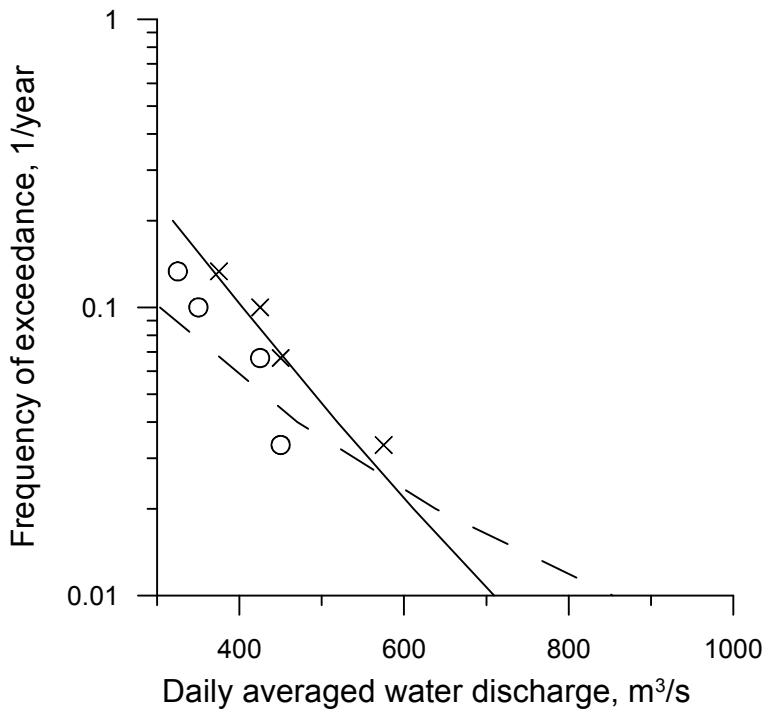
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7 Fig. 8 Exceedance frequency of extreme daily average water discharges in Uzhgorod for the period of 1960-1990; '×' – results

8 of measurements; black line corresponds to CCDF obtained by fitting measurements with GEV distribution; 'o' – results of

9 calculations; dashed line corresponds to CCDF obtained by fitting the results of calculations with GEV distribution