2006

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SIMULATION OF THE SUPERIMPOSITION OF FLOODS IN THE UPPER TISZA REGION

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Abstract. Major floods on the Upper Tisza down to the confluence of the main river with the Bodrog tributary usually result from the superimposition of several flood waves arriving from upstream sections and their coincidence with floods on the tributaries. This phenomenon was the basis for simulation exercises which were carried out for a limited number of scenarios generated by the combination of a few historical events. A more complex approach using a hybrid seasonal Markov-chain model for daily streamflow generation was also applied in combination with the DLCM-based flood routing system of the complex river network. Diurnal increments of the rising limb of the main channel hydrograph, increments of the rising hydrograph values at the tributary sites, and the recession flow rates of the tributaries as well as of the main channel were identified and subject to various statistical analyses. The model-generated daily values retained the short-term characteristics of the original measured time series as well as the probability distributions and basic long-term statistics of the measured values. Such results describe possible future scenarios of flood events and may help water managers prepare for events that have not yet been recorded in the past, but could be expected in the future.

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J. Marsalek et al. (eds.),
Transboundary Floods: Reducing Risks Through Flood Management, 171–182.

Keywords: superimposition of floods, flood routing, streamflow generation models, Markov chains, hydrographs

1. Introduction

Hydrologists involved in operational stream forecasting and flood control may be interested in possible future scenarios of flood events. This may help them prepare for events that have not yet been observed in the past, but nonetheless could be expected in the future. While statistical analyses of e.g., annual maxima may yield information on return periods of floods of different magnitudes, they do not provide information on the possible time-sequence of the expected flood events. Such information may encompass duration of different water levels during flood, and the speed at which stream levels may rise or the flood may recede, all of which potentially influences the planning and organisation of flood protection works.

Major floods on the Upper Tisza down to the confluence of the main river with the Bodrog tributary (the Tokaj station) usually result from the superimposition of several flood waves from upstream sections and their coincidence with floods on the tributaries. This phenomenon was the basis for simulation exercises which were carried out for a limited number of scenarios generated by the combination of a few historical events (Bartha et al. 1998; Gauzer and Bartha 1999, 2001; Harkányi and Bálint 1997). These studies clearly indicated the possibility of unfavourable coincidences of floods; however, no estimates of frequency are associated with individual scenarios. Relatively short observed time series on the Tisza and tributaries (less than 150 years for water levels and less than 100 years for discharges) leave no space for attempts to include bi- or multi-dimensional distributions. To overcome these difficulties, a more complex approach using a Monte Carlo simulation for the upper boundary stations for daily streamflow generation, in combination with the DLCM based flood routing system used in the forecasting and modelling system of the National Hydrological Forecasting Service of Hungary, VITUKI, was used for the Upper Tisza river network (Figure 1).

Our multivariate, seasonal streamflow generation algorithm detailed below uses components of the shot noise models in a Markov-chain based approach together with a conceptual framework describing flow recession without the need for knowing precipitation. It is built around the concept of conditional heteroscedasticity, which was originally established in the ARCH models of time series analysis by assuming that the noise term was not independent of the process to be modelled or identically distributed (Engle 1982).

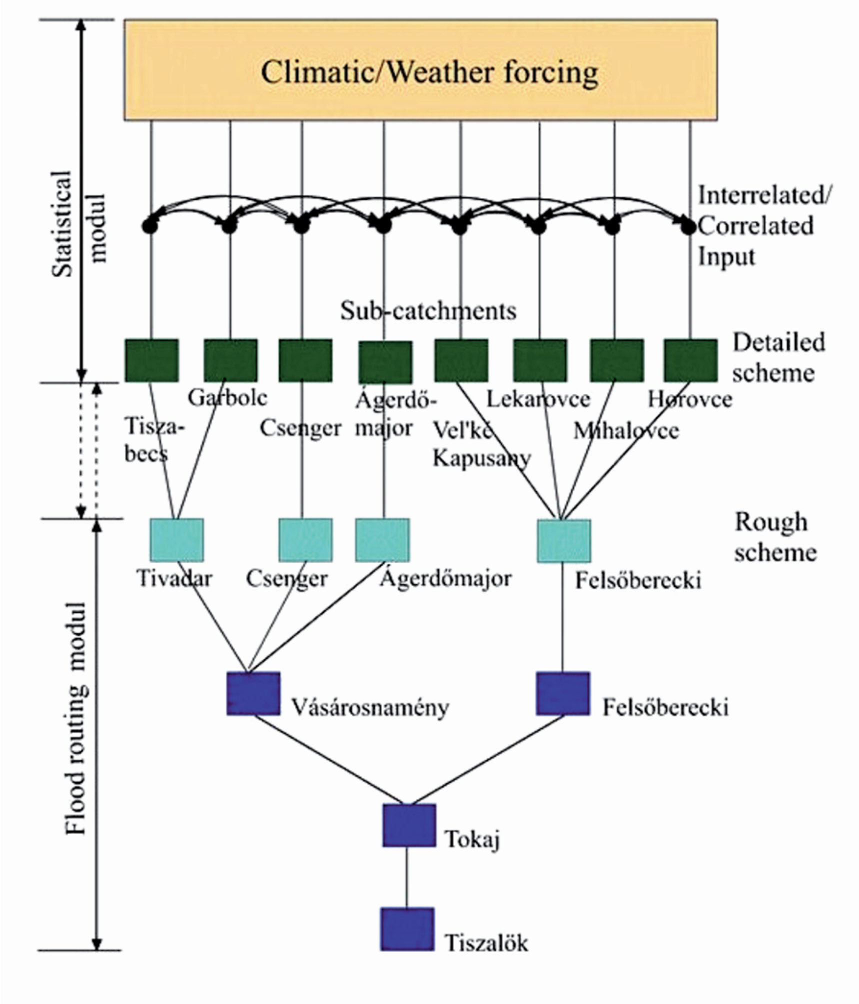

Fig. 1. General scheme for simulation of flood events on the Upper Tisza

2. Formulation of a hybrid Markov-chain model

The model works with daily streamflow data from which a time series of diurnal increments can be obtained by differentiating the original series. These increments define a two-state Markov chain for perennial streams. State one is observed when the increment is positive (termed as the "wet" state), and state two (termed as "dry") occurs when the increment is negative. The two states result in four different state transitions: wet-wet (P_{ww}), wet-dry (P_{wd}), dry-wet (P_{dw}), and dry-dry (P_{dd}). The state transition probabilities can be estimated from the observed data as

$$P_{ij} = \frac{n_{ij}}{\sum_j n_{ij}}; \qquad i, j = w, d \tag{1}$$

The state transition probabilities typically vary with seasons. Often these transitions are written on a monthly basis (e.g., Xu et al 2001, 2003), which results in very similar values between the neighbouring months, thus raising the question whether they are statistically different or not. From the viewpoint of parameter parsimony, a seasonal resolution should suffice in most cases, and this approach was adopted here.

2.1. RISING LIMB OF THE HYDROGRAPH

Positive diurnal increments (or wet states) designate the rising limb of the hydrograph. Sargent (1979) and Aksoy (2003) recommended a two-parameter gamma distribution for these increments. For the largest tributary of the Danube in Hungary, the Tisza River, and its tributaries, the Bodrog, Szamos, and Kraszna Rivers (Figure 1), a Weibull distribution fits well the observed data collected from 1951 to 2000.

During Monte-Carlo simulation of these increments ($dQ\ [L^3T^{-1}]$) for wet states the computer uses the fitted distributions (on a seasonal basis) for random number generation. The values obtained for the main channel, which is the Tisza River, are subsequently perturbed with an additional noise term ($W\ [L^3T^{-1}]$), taken from a normal distribution of zero mean (m). The noise, however, is not identically distributed, because its standard deviation is conditioned on the Weibull-distributed random number (dQ_{gen}) to be perturbed

$$W(m, \sigma) = W(0, a \cdot dQ_{gen}^{\ b}) \tag{2}$$

where $a\ [L^{3(1-b)}T^{(b-1)}]$ is a scale-coefficient, and $b\ [-]$ is an exponent. The noise values that are negative and have larger magnitudes than the corresponding dQ_{gen} values, are discarded and replaced by zero. This makes the noise values to follow a positively skewed distribution, of which mean is no longer zero. The scale coefficient, a, and the exponent, b, are model parameters to be optimised. This so-called conditional heteroscedasticity assures that the Monte-Carlo generated diurnal increments will have a similarly wide range of values as the observed ones.

Another alternative could be the use of a noise term that follows the Weibull rather than normal distribution. In that case the prescribed mean and standard deviation of the distribution (the latter providing a rough idea of the spread of the distribution) could be converted to the parameters of the distribution. However, the Weibull distribution is a monotonic function for a wide range of parameters, while the distribution of the diurnal increments generally is not. Consequently, it is more convenient to employ a normal distribution instead, and make it skewed by specifying the lower limit with each value of the increment to be perturbed.

Once the positive increment values have been generated for a wet spell, they are ranked in an increasing order to make sure that the larger increments are closer to the peak of the hydrograph. This recreates the general shape and ensures preservation of the correlation structure of the rising limb of the hydrograph (Aksoy 2003).

Typically, tributary flow values are correlated with the main channel values; therefore, one may want to avoid generation of positive increment values for the tributaries separated from the main channel. One way of linking tributary increments to the main channel state could be achieved by conditioning the state transitions of the tributaries to that of the main channel, since for a correlated flow series the probability of a wet-to-wet transition is higher for the tributary when the main channel is in a wet state too. Unfortunately, such conditioning of the state transition probabilities did not meet expectations in our study: the cross-correlation value between the (measured) main channel and simulated tributary flow rates remained much lower than observed. As an alternative, the procedure described in the following section was performed.

Diurnal increments of the rising hydrograph at the tributary sites and at the main channel were described by second-order polynomials. The polynomial-derived tributary increment values were again perturbed by an additional noise term in eq. (2), similar to the main channel case. Note that, as before, eq. (2) includes dQ_{gen} of the main channel and not of the tributary. Alternatively, one may chose to use the polynomial-derived tributary value instead of dQ_{gen}. In either case, the coefficients, a and b, must be optimised for each tributary site.

2.2. RECESSION CURVE

Drainage of stored water from the channel is generally a nonlinear process (Aksoy et al. 2001). Often a nonlinear reservoir approach is used

$$Q = kS^n \tag{3}$$

where Q $[L^3T^{-1}]$ is observed streamflow, k $[L^{3(1-n)}T^{-1}]$ is a storage coefficient, S $[L^3]$ is stored water volume, and n $[-]$ is an exponent. During recession flow the value of the exponent may change (Kavvas and Delleur 1984) with time. As an alternative, rather than changing *n* through time, the value of *k* may be changed (Aksoy et al. 2001; Aksoy 2003) with *n* chosen equal to one, and in this case, eq. (3) can be rewritten in a differentiated form as

$$\frac{dQ}{dt} = -kQ \tag{4}$$

which has a solution (up to an arbitrary constant)

$$Q(t) = Q_0 e^{-kt} \tag{5}$$

that can be written for $t = 1$ day and with the $Q_0 = Q(t\text{-}1)$ choice as

$$Q(t) = e^{-k'} Q(t-1) = c_1 Q(t-1) \tag{6}$$

where $k'(= 1\ k)$ [-]. Employing a finite difference approximation of eq. (4) with $t = 1$ day yields

$$Q(t) = (1 - k')Q(t-1) = c_2 Q(t-1) \tag{7}$$

which shows that by proper choice of c_2 in the finite difference scheme one can obtain the analytical solution of eq.(6). By letting the value of *k'* in eq. (7) change in time, one can simulate the outflow of a nonlinear reservoir having a time variable exponent. The following expression permits the value of c_2 to increase in a logarithmic fashion from a minimum value at the time of the peak of the hydrograph to close to 1, if k'_{min} is chosen sufficiently small

$$Q(t) = Q(t-1)\left[1 - k'_{min} - \frac{k'_{max} - k'_{min}}{\ln\left(\frac{Q_{max}}{Q_{min}}\right)} \ln\left(\frac{Q(t-1)}{Q_{min}}\right)\right] \tag{8}$$

Note that when $Q(t-1) = Q_{max}$, $c2 = 1- k'_{max}$; and when $Q(t-1) = Q_{min}$, $c2 = 1 - k'_{min}$. Eq. (8) assures that the recession is steeper than a negative exponential function, and so it fits observations (Kavvas and Delleur 1984).

The above description of recession flow cannot account for year-to-year variations in the volume of groundwater stored in the catchment. During wet years this additional source of water will prevent very low flow rates in the channel for perennial streams. The model accounts for this variability by adding a stochastic groundwater component to the recession flow model descried by eq. (8) in the form

$$Q_{gw}(t) = (1 - k'_{\min})Q_{gw}(t-1) \tag{9}$$

where Q_{gw} designates the groundwater contribution to the channel flow, which is the sum of eqs. (8) and (9) during recession flow periods. The starting value of Q_{gw} with a wet-to-dry transition at time t is obtained as

$$Q_{gw}(0) = \left| W(d \cdot Q_{gen}(t), f \cdot Q_{gen}(t) \right| \tag{10}$$

where, again, *d [-]* and *f [-]* are parameters to be optimised; and W is a normally distributed variable. The straight brackets denote the absolute value. In theory the multiplier of Q_{gw} in eq. (9) could change with time as in the channel flow case (Brutsaert and Nieber, 1977; Szilagyi 1999, 2004), but that would further complicate the model which is intended to be kept as simple as possible.

The model has altogether 8 parameters to be specified. Two of them, Q_{max} and Q_{min}, are the observed extremes and can be specified during Monte-Carlo simulation to be somewhat larger and smaller, respectively, than their historical values, in order to accommodate possibly larger or smaller generated values than observed. From the remaining six parameters only a is dependent on the season and even then only for the main channel. The remaining parameters are constant during the year.

3. Model results

The Tisza River is the major tributary of the Danube in Hungary (Figure 1). Besides the gauging station of Tivadar on the Tisza River, three additional sites on different tributaries of the Tisza were included in this preliminary stage of the study. Fifty years (1951-2000) of daily instantaneous flow-rate values were employed for all four gauging stations representing the upper limit of the 'coarse scheme' (Figure 1). Table 1 displays the estimated state transition probabilities at Tivadar on a seasonal basis. It shows that a wet-to-wet transition has the highest likelihood in spring, which comes from two sources: (a) it is the season of most abundant precipitation in Hungary; and (b) it is the time of year when melting snow in the Carpathian Mountains feeds the streams, occasionally (especially when combined with rain) causing major flooding in the region. The positive diurnal increment values at Tivadar were fitted with Weibull distributions for each season and randomly generated using those distributions. For each increment a W value (eq. [2]) was added, with optimised values of a (= 1.1, 1.2, 1, 0.7, for the four seasons, starting with winter) and b (= 1). For each wet spell these values were sorted in an ascending order. Figure 2 displays the Q-Q plots of observed and generated positive diurnal increment values for the four seasons.

Table 1. Estimated state transition probabilities (%) at Tivadar

	P_{dd}	P_{dw} (= 1 - P_{dd})	P_{wd}	P_{ww} (= 1 - P_{wd})
Winter	80.44	19.56	37.9	62.1
Spring	79.71	20.29	37.55	62.45
Summer	76.15	23.85	51.34	48.66
Fall	80.51	19.49	48.62	51.38

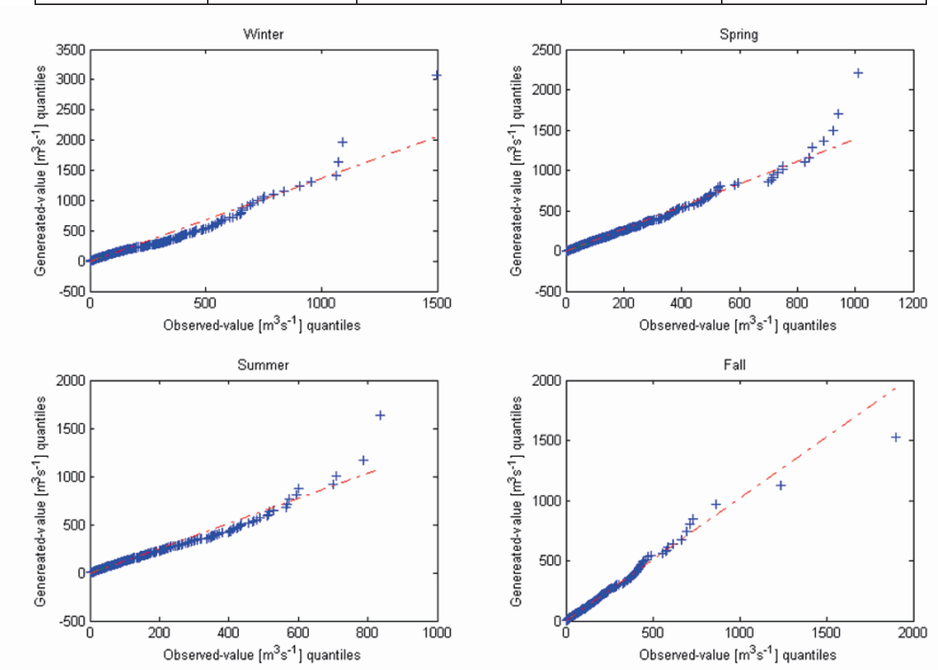

Fig. 2. Seasonal Q-Q plots of observed and generated positive diurnal increment values of the Tisza River at Tivadar

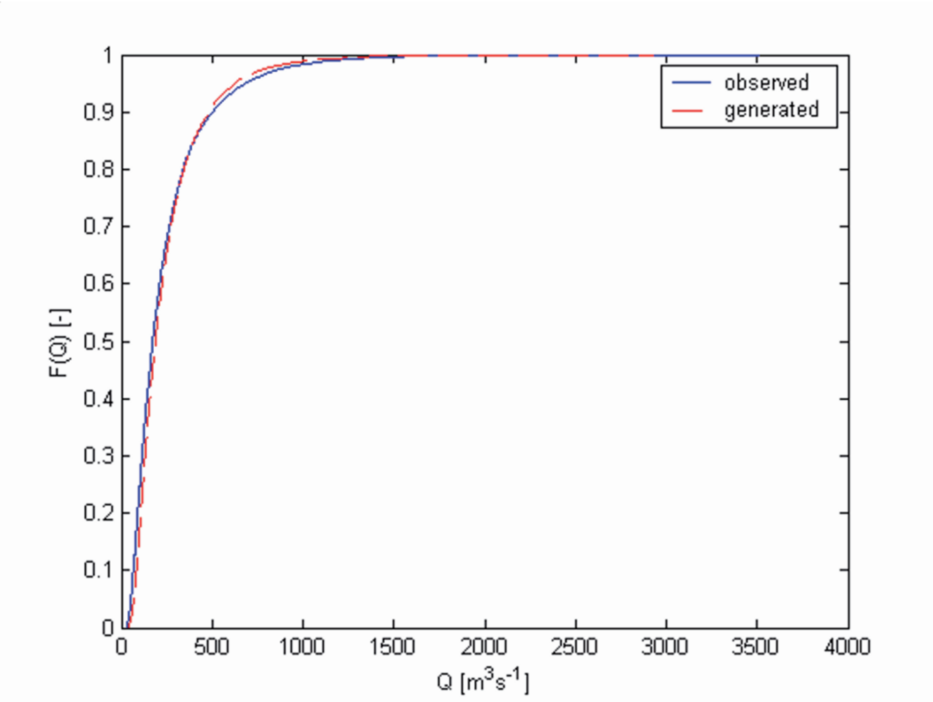

Fig. 3. Empirical cumulative distribution functions of 50 years of observed and simulated daily flow rates of the Tisza River at Tivadar

Recessions were modelled with $k'_{max} = 0.33$, $k'_{min} = 0.015$, $d = 0.04$, and $f = 0.02$. Comparison of observed and generated time series of daily discharges at Tivadar proves that the asymmetric shape of the observed hydrographs is well preserved in the generated data. Empirical cumulative distribution functions of 50 years of observed and simulated daily flow rates are demonstrated in Figure 3. Distributions of the annual maxima, means, and minima are also well preserved (Figure 4). A good agreement between observed and simulated flow rates for each season, the annual change in the median values (i.e. elevated water levels in spring, low flows in autumn), and the skewness of the rates was found. Finally, Figure 5 shows the autocorrelation functions for 50 years of observed and simulated daily flow values of the Tisza River at Tivadar.

Simulation of the tributary flow differs from that in the main channel only in the application of a polynomial regression between the tributary and main channel diurnal increments during wet spells of the main tributary in place of a Markov approach of state transition probabilities.

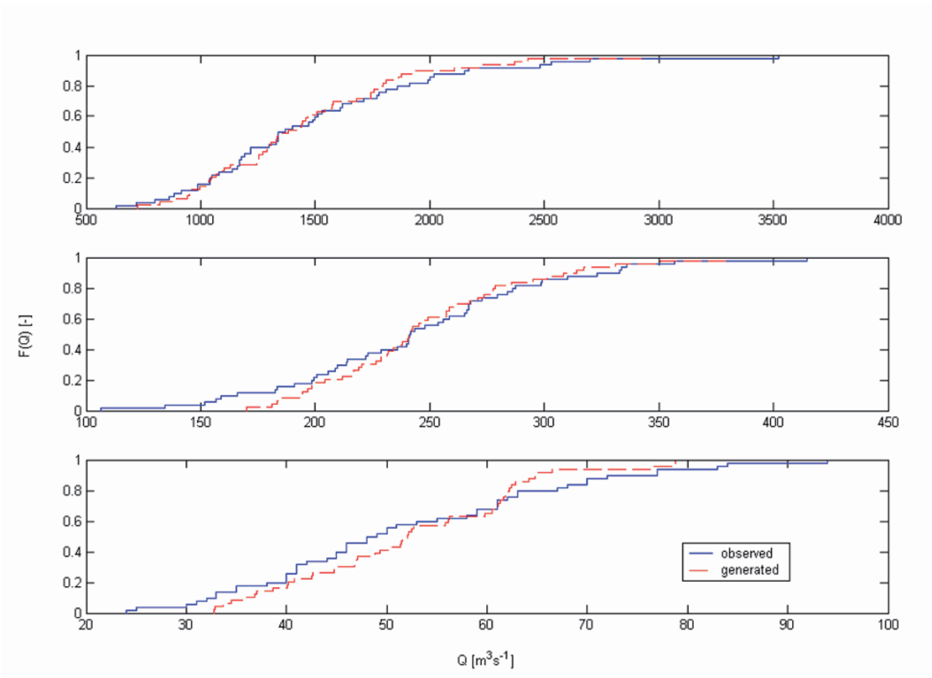

Fig. 4. Empirical cumulative distribution functions of 50 years of observed and simulated annual maxima, means, and minima of daily flow rates of the Tisza River at Tivadar

In summary it can be stated that by the application of the proposed hybrid, seasonal Markov-chain approach to daily flow simulation at multiple catchment sites it is possible to generate arbitrarily long time series of daily flow rates that fairly well preserve basic long-term (mean, variance, skewness, autocorrelation structure, and cross-correlations) statistics as well as the short-term behaviour (asymmetric hydrograph) of the original time series. The approach is centred on the concept of conditional heteroscedasticity which means that the noise term of the stochastic model applied is not independent of the process to be modelled, and it is not identically distributed. The model has altogether 9 parameters (in a seasonal formulation) for the main channel site to be optimised, and 6 additional parameters for each gauging station to be included. While the described approach is very simple, optimisation of the parameters may require some effort from the modeller.

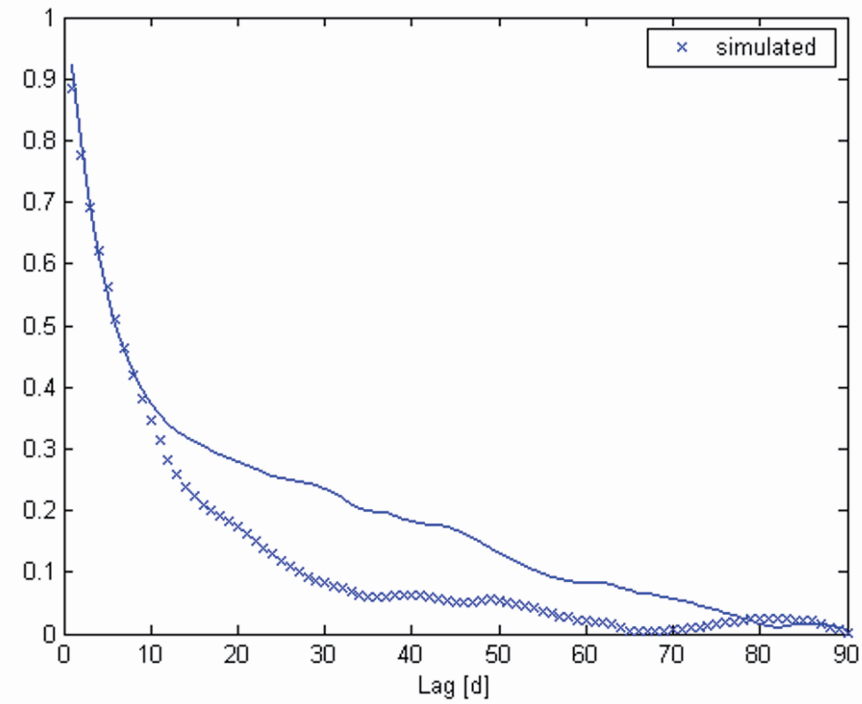

Fig. 5. Autocorrelation functions of 50 years of observed and simulated daily flow values of the Tisza River at Tivadar

Acknowledgment

This work has been supported by the Hungarian Research and Development Project: "Flood Risk Analysis", NKFP 3/067/2001.

Disclaimer

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