Rainfall-runoff model for design flood computation with variable parameters

S. Ignar en J.J. Bogardi

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Vakgroep Waterhuishouding
Nieuwe Kanaal 11, 6709 PA Wageningen

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CONTENTS

1. INTRODUCTION

Analysis of development and movement of flood flows is one of the most important subjects in hydrological research. Conducted investigations are aimed to recognize the particular processes involved in flood forming, their formal description and efforts to model them. A properly developed model, being a simplified description of the real the watersheds system, allows to determine watershed reaction on rainfall as an input impulse. Modeling methodology makes also possible to investigate all changes, including antropogenic and climatic ones in the watershed, and their impact on flood flows. The main problem of mathematical modeling of small watersheds - the lack of recorded data - can be overcomed by applying simple, conceptual rainfall-runoff models with only a few parameters. Parameters of these models can be determined from correlation formulae and topographic maps. Such models allow for usage of the unit hydrograph method for computation of flood caused by estimated rainfall. The proposed model will be applied to four small catchments in Poland.

2. DESCRIPTION OF THE MODEL

2.1. GENERAL COMMENTS

This report describes the investigation and development of a conceptual model for design flood evaluation with assumed probability of occurrence. The proposed methodology is based on transformation of the rainfall with assumed probability of occurrence into flood hydrograph. It is a modified version of the conceptual model described by Ignar (1986). The original version of the model consists of three sub-models leading to evaluation of:

a) total rainfall - P

b) effective rainfall - H

c) direct flow hydrograph - Q

It requires from the user the arbitrary assessment of different parameter sets for the three sub-models. Such an arbitrary assessment is often criticized as it does not ensure the equality of probabilities for input rainfall and computed flood. It is because calculated flood with assumed probability can be caused by one of many possible combinations of rainfall depth, time distribution and duration and areal variability. To solve these problems a simulation technique is proposed, which allows to apply many sets of sub-model parameter values for assumed probability distributions of these parameters (Beran 1973). The proposed technique consists of the following stages:

a) assuming of event probability,
b) random selection of rainfall duration,
c) evaluation of total rainfall depth from relations between the above assumed probability, selected duration and depth of rainfall,
d) assuming of time distribution for rainfall,
e) selection of CN parameter value and effective rainfall evaluation by SCS method,
f) transformation of effective rainfall into flood flows,
g) determination of statistical distribution for computed floods.

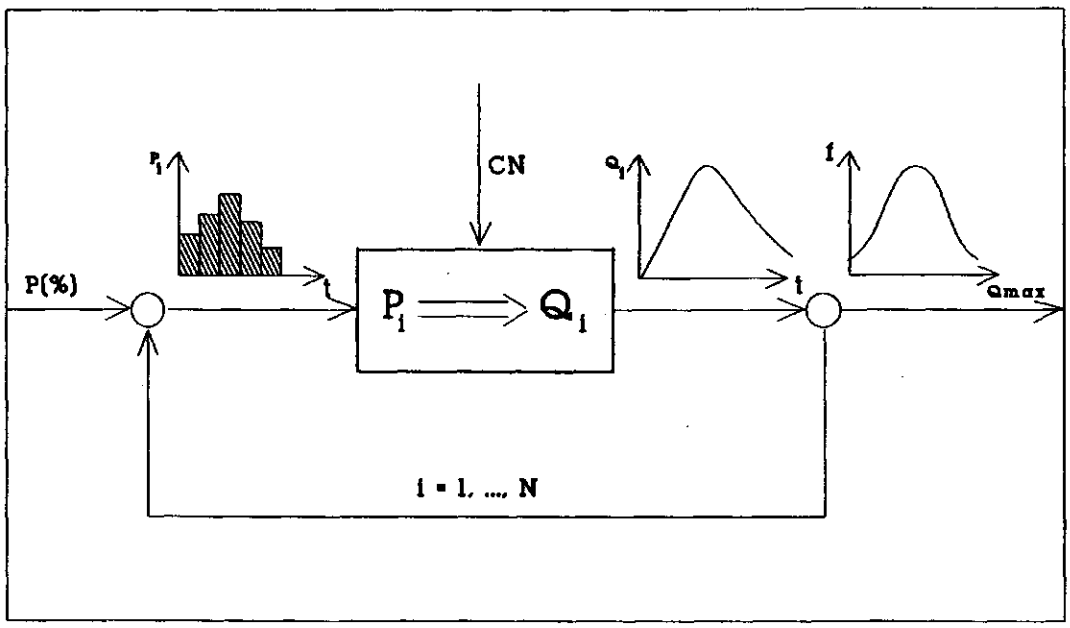

Figure 1. Model structure

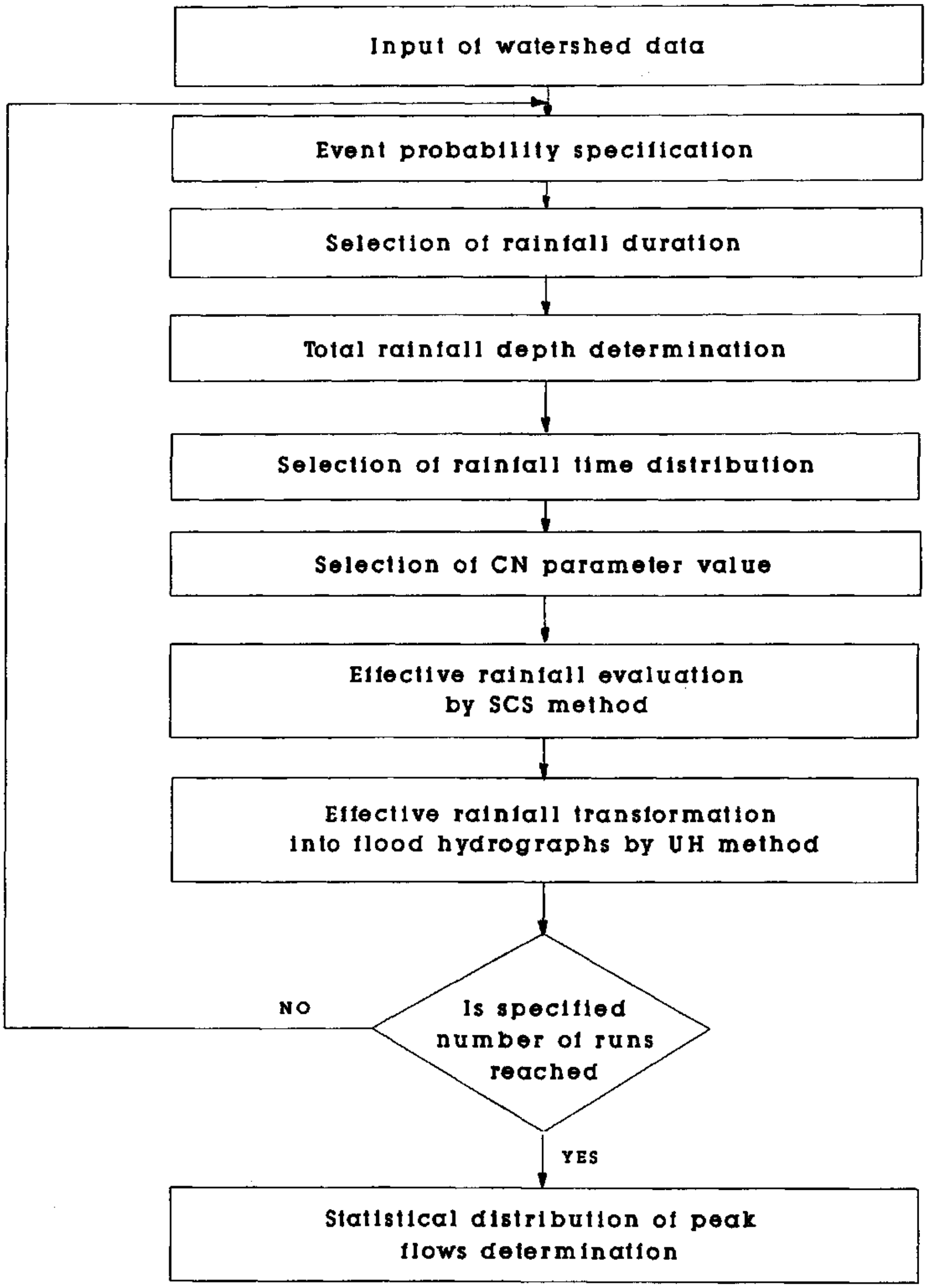

Figure 2. Flowchart of the proposed procedure

Stages from b to f will be repeated by a prespecified number of times and for each recurrence values of rainfall duration, depth, distribution and parameter for effective rainfall determination method will be evaluated by random number generator from assumed statistical distributions of these values. The parameters of the above mentioned probability distributions were derived from empirical data. The proposed model structure is shown in figure 1 and its flowchart in figure 2. The procedure has been programmed in PASCAL language for PC/AT microcomputer as a modular package.

2.2. TOTAL RAINFALL EVALUATION

In order to describe the input rainfall characteristics for the proposed procedure, the probability of occurrence, duration, intensity and time distribution have to be determined. Design probabilities are assumed in accordance with the importance of the designed structure and range of damages caused by its possible failure. These probabilities fall within the range from 0.1% to 3% for various regulations in Poland. Duration of rainfall is usually taken to be equal to the time of concentration for an analyzed watershed, assuming that it would cause the biggest flood flow. Simulation computations of floods have shown, that this assumption was not valid for most of the cases (Banasik, Ignar 1986). In the proposed procedure the rainfall duration will be randomly taken from probability distribution in order to avoid this disadvantage.

The rainfall data recorded for Wadowice weather station in south part of Poland were analyzed. Eight years of hourly sums were tested taking into account all rainfalls higher than 5 mm (total per event) and lasting longer than 3 hours. 179 events fulfilling these criteria were collected. Average duration of 8 hours with the standard deviation equal to 5.6 h were obtained. The transformed variable:

$$t' = (t - 2)^{1/3} \qquad \ldots 2.1$$

(where t denotes the observed storm duration) has been found to fit the normal distribution function. The average value of t' was 1.674 and the standard deviation was 0.502.

The mean intensity of total rainfall is deterministically related to its duration and probability. Such a dependence can be described by the general formula (Raudkivi 1979):

$$J = \frac{k \cdot T^{x}}{(t + c)^{n}} \qquad \ldots 2.2$$

where:

J - rainfall intensity (mm/h),
t - rainfall duration (h),
T - return period (years),
k, x, c, n - regional and climatic coefficients.

Regional and climatic coefficients in formula 2.2 and its modifications are determined empirically by using rainfall records. For the proposed procedure the indirect method developed for Poland by Stachy (1976) was adopted. Rainfall intensity is evaluated by the equation:

$$J_{p,t} = \Psi(t) \cdot P_{p} \qquad \ldots 2.3$$

where:

Jp,t - rainfall intensity (mm/h),
p - rainfall probability (%),
t - rainfall duration (h),
P_p - daily maximum rainfall with probability p (mm),
$\Psi(t)$ - reduction function value for duration t (1/h).

The reduction function form was developed by Stachy for Poland using available data.

Total rainfall intensity is not constant in time and the often used rectangular rainfall distribution scheme can lead to serious errors in computed flows. There are quite a lot of "typical" storm distribution patterns shown in literature. All of them have been obtained from recorded data analysis. Rainfall distribution pattern described by dimensionless mass curve was adopted for the proposed algorithm (Ignar, Węglarczyk 1991). Such a model can be formulated as follows: for each total rainfall P (mm) with duration T (hour) and mass curve h(ta) (mm) ($ta \varepsilon [0,T]$, $h(0) = 0$, $h(T) = P$) it is possible to define by equation 2.4 the rainfall dimensionless mass curve $h^*(ta^*)$, where $h^* \varepsilon [0,1]$ is a dimensionless height of rainfall and $ta^* \varepsilon [0,1]$ is a dimensionless rainfall duration:

$$h^*(ta^*) = \frac{h(ta)}{P} \qquad t^* = \frac{ta}{T} \qquad \ldots 2.4$$

There are following assumption to define a model:

1. Each single rainfall event with height and duration normalized to unit can be described by deterministic unimodal function $h^*(t^*;\alpha,\beta)$ as a normalized incomplete beta function:

$$h^*(t^*;\alpha,\beta) = \frac{1}{B(\alpha,\beta)} \int_0^{t^*} (t^*)^{\alpha-1} \cdot (1-t^*)^{\beta-1} dt^* \qquad \ldots 2.5$$

where:

$B(\alpha,\beta)$ - Euler beta function,
$h^*(0) = 0$, $h^*(1) = 1$,
$\alpha > 0$, $\beta > 0$ - function parameters.

2. Parameters α and β in function 2.5 are probabilistic variables from general population (A, B) with probability distribution described by $f_{AB}(\alpha,\beta)$. Two dimensional, five parameters log-normal distribution $f_{AB}(\alpha,\beta$, avA, sdA, avB, sdB, rAB) was found as the most suitable for description of probabilistic vector (A, B) distribution. Parameter values for the analyzed set of rainfall data from Wadowice were determined as:

avA - average value for A - 0.660,
sdA - standard deviation for A - 0.983,
avB - average value for B - 0.891,
sdB - standard deviation for B - 0.822,
rAB - correlation coefficient between A and B - 0.773.

2.3. EFFECTIVE RAINFALL CALCULATION

The method for effective rainfall determination is a very important part of any rainfall-runoff modeling technique. The effective rainfall H is defined as a part of total rainfall remaining after withdrawing of losses consisting of: infiltration, evapotranspiration, interception and depression storage. Among the many methods used in engineering hydrology the SCS (Soil Conservation Service) Curve Number method was adopted in the proposed procedure. This method was fully described by SCS (NEH 1985). The depth of effective rainfall, H is subjected to the CN parameter depending on: soil type, land use, soil conservation practices and antecedent moisture conditions. This parameter is related to the maximum retention, S in mm:

$$S = 25.4 \cdot \left(\frac{1000}{CN} - 10 \right) \qquad ...2.6$$

and effective rainfall can be calculated from the simple empirical formula:

$$H = \frac{\left(P - 0.2 \cdot S \right)^2}{P + 0.8 \cdot S} \qquad ..2.7$$

where:

P - total rainfall depth (mm).

Using this formula it is possible to determine the effective rainfall in subsequent time intervals. The value of the CN parameter can be evaluated from soil maps and tables developed by SCS (NEH 1985).
Variability of CN value for particular floods is caused mostly by differences in initial wetness of watershed and in SCS method it is taken into account by calculating rainfall totals for five days before the analyzed flood. There are three levels of antecedent moisture conditions (AMC) and it seems to be not enough flexible for real life conditions. Hawkins et al (1985) proposed to apply a log-normal distribution which can be adopted for describing the distribution of the CN values according to different moisture conditions. Such a distribution was adopted for this proposed procedure for random evaluation of CN values.

2.4. RAINFALL RUNOFF TRANSFORMATION

Among the many existing rainfall-runoff models the Wackermann conceptual model of two parallel cascades consisting of two linear reservoirs was adopted for rainfall runoff transformation (Ignar 1986). It is a special case of a more general Diskin (1964) model. Parameters of these model (i. e. K1, K2 - retention coefficients for the first and second cascades, and β - dividing coefficient for input effective rainfall) can be evaluated from the formulae developed by DVWK (1984) from data recorded in over 90 watersheds situated in the western part of Germany. Avaliable recorded data from 13 agricultural watershed in Poland were collected by the authors for the Wackermann model parameter evaluation in order to find similar empirical formulae. Total number of 60 flood events were gathered, with at least 3 for each watershed. The watershed description summary is shown in Table 1. Model parameters values were calculated by the optimization method based on Rosenbrock technique. Correlation formulae similar to these obtained by DVWK were developed for optimized parameter values using the least squares method:

$$\beta = 0.04 \cdot \left(\frac{L}{\sqrt{I}}\right)^{-0.403} \qquad \ldots 2.8$$

$$K1 = 1.28 \cdot \left(\frac{L}{\sqrt{I}}\right)^{0.159} \qquad \ldots 2.9$$

$$K2 = 0.892 \cdot \left(\frac{L}{\sqrt{I}}\right)^{0.379} \qquad \ldots 2.10$$

where:

L - the horizontal projection of the channel length from the most distant point to the basin outlet (km),

I - slope between these two points (-).

Then, verification calculations were conducted with the use of independent data from 8 observed watersheds, listed in Table 2. 55 rainfall-runoff events for these watersheds were collected. The criterion proposed by Delleur et al. (1973), so-called special correlation coefficient (Rs) was used for comparison of observed and simulated hydrographs. The authors of the criterion determined five intervals making it possible to evaluate the agreement between the observed hydrographs and the one computed by the model, by using five grades from excellent (denoted by 5 to poor (denoted by 1). These intervals are:

$0.99 \leq Rs < 1.0$	excellent = 5
$0.95 \leq Rs < 0.99$	very good = 4
$0.90 \leq Rs < 0.95$	good = 3
$0.85 \leq Rs < 0.90$	fair = 2
$0.00 \leq Rs < 0.85$	poor = 1

There were: one very good grade, three good, one fair and three poor among 8 tested watersheds. Based on this evidence the derived formulae have been adopted for proposed model.

Table 1. Optimized Watersheds Description Summary

No	**WATERSHED**	**Profile**	Area km^2	Channel length km	Levels difference m
1	Zagożdżonka	Wygoda	9.3	6.6	14.0
2	Czarna Woda	Jaworki	11.7	9.4	702.0
3	Mława II	Uniszki	18.2	5.0	31.0
4	Leśnianka	Lipowa	21.5	6.2	628.0
5	Trzebuńka	Stróża	30.4	10.7	563.0
6	Bóbr	Bukówka	58.5	9.4	599.0
7	Wisła	Ustroń	108.2	20.3	820.0
8	Bolszewka	Bolszewo	221.1	25.9	90.3
9	Wilga	Oziemkówka	231.6	23.6	59.0
10	Skawa	Osielec	239.7	37.1	973.0
11	Soła	Rajcza	254.0	16.8	840.0
12	Nysa Kłodzka	Bystrzyca	260.2	34.6	1084.0
13	Łososina	Jakubkowice	342.6	49.4	922.0

Table 2. Verification Calculations Summary

No	WATERSHED	Profile	Area km^2	Channel length km	Levels difference m	RS	grade
1	Mławka IV	Uniszki	35.5	5.35	31.7	0.460	1
2	Moszczeniczka	Pieszcz	67.7	15.90	42.0	0.979	4
3	Skierniewka	Borysław	98.2	17.30	48.9	0.900	3
4	Świślina	Rzepin	118.0	28.20	152.9	0.919	3
5	Czarna Orawa	Jabłonka	136.0	24.30	328.0	0.794	1
6	Raba	Mszana Dln.	161.7	30.00	599.4	0.770	1
7	Mszanka	Mszana Dln.	174.6	15.60	939.2	0.872	2
8	Kwisa	Mirsk	185.6	19.70	785.0	0.902	3

3. PRACTICAL APPLICATIONS AND CONCLUSIONS

3.1. GENERAL COMMENTS

Verification of a model is one of the most important stages in the model developing process. It allows for evaluating the model quality by comparing actual watershed output with model output, and for assessing the practical applicability of hydrological computations.

Verification of the model was conducted by comparison of empirically calculated probability curves with simulated ones. A sensitivity analysis was also performed, accompanied by a simulation calculation for anthropogenic influences on flood flows.

3.2. VERIFICATION OF COMPUTATIONS

Verification of computations have been conducted for four small basins located in the Carpatian Mountains. Table 3 shows the basic information concerning the basins. Empirical probability curves were developed by a standard statistical method assuming a Pearson type III distribution. Developed curves are shown in figures 3 to 6, together

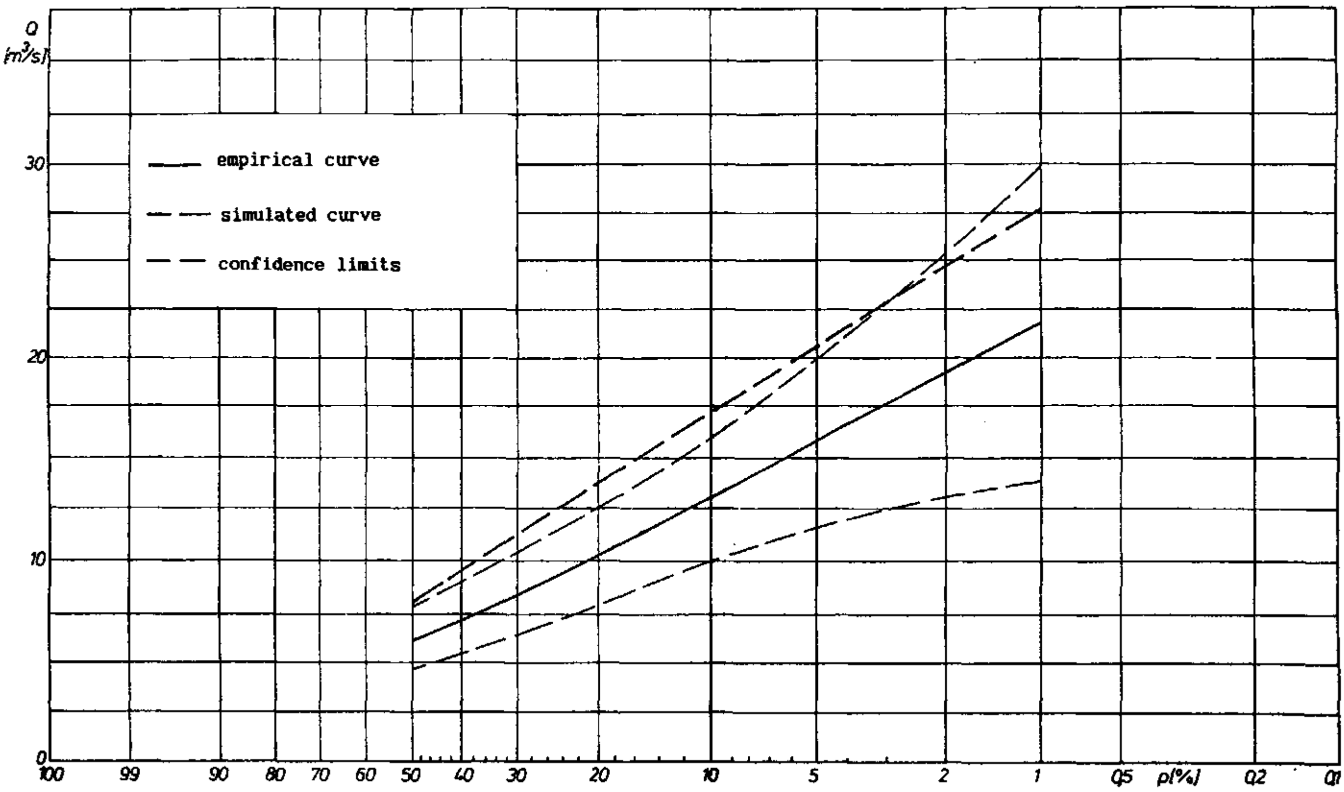

Figure 3. Comparison of probability curves for river Leśnianka profile Lipowa

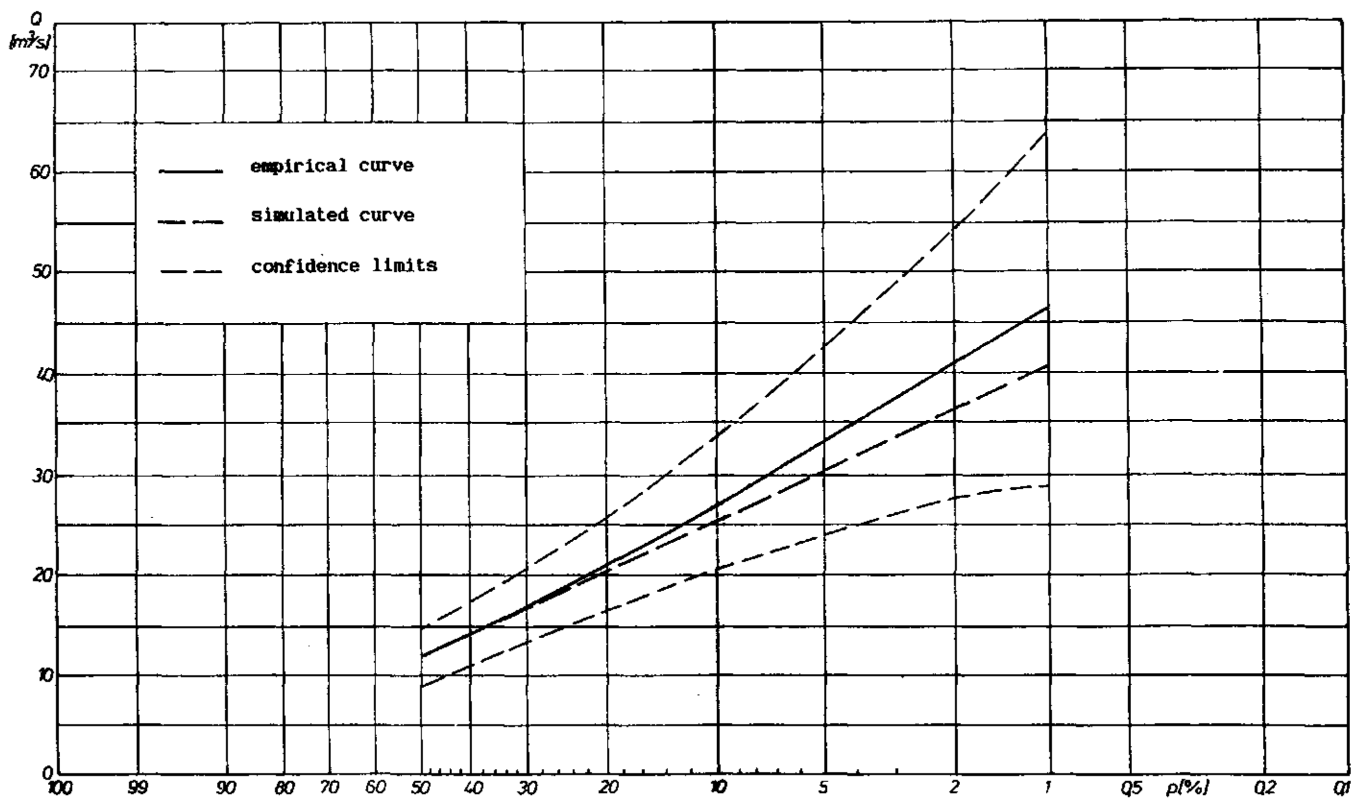

Figure 4. Comparison of probability curves for river Lubieńka profile Lubień

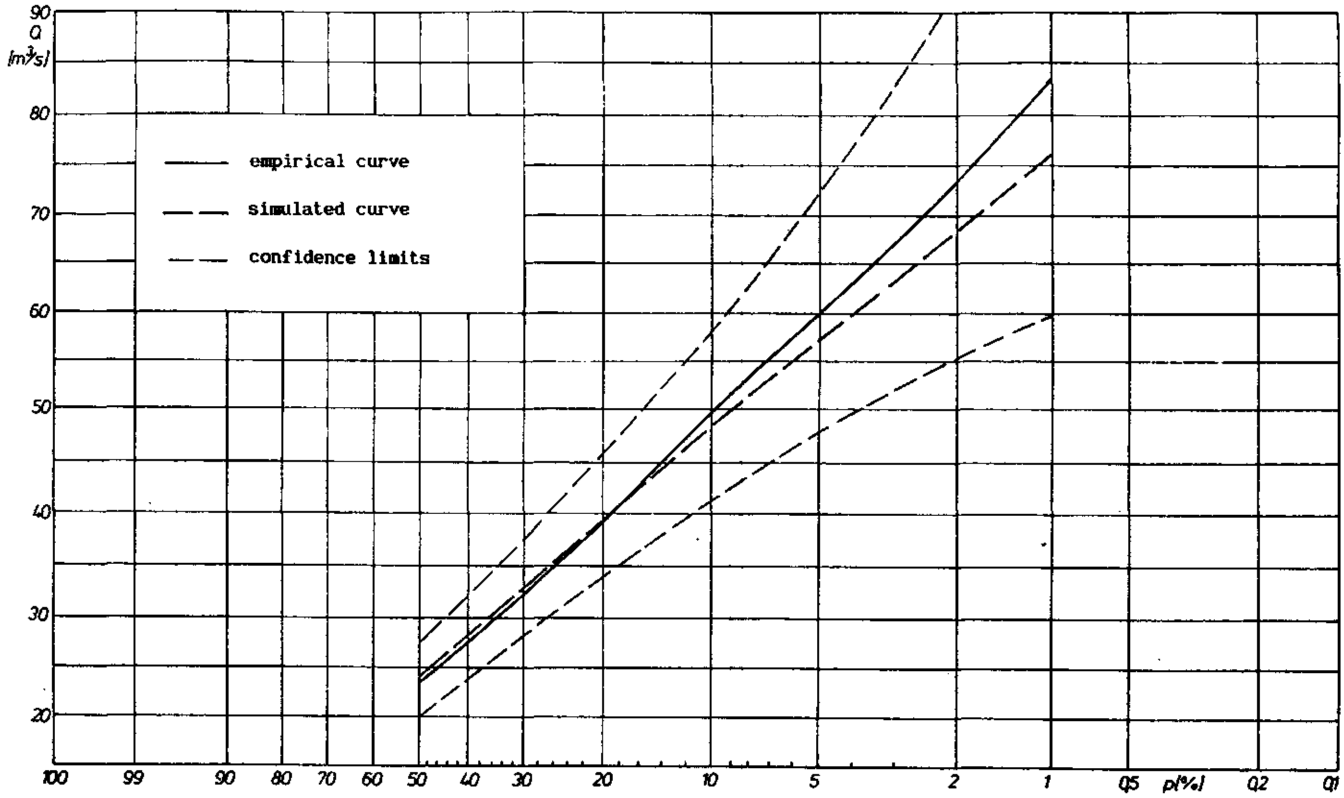

Figure 5. Comparison of probability curves for river Wisła profile Wisła

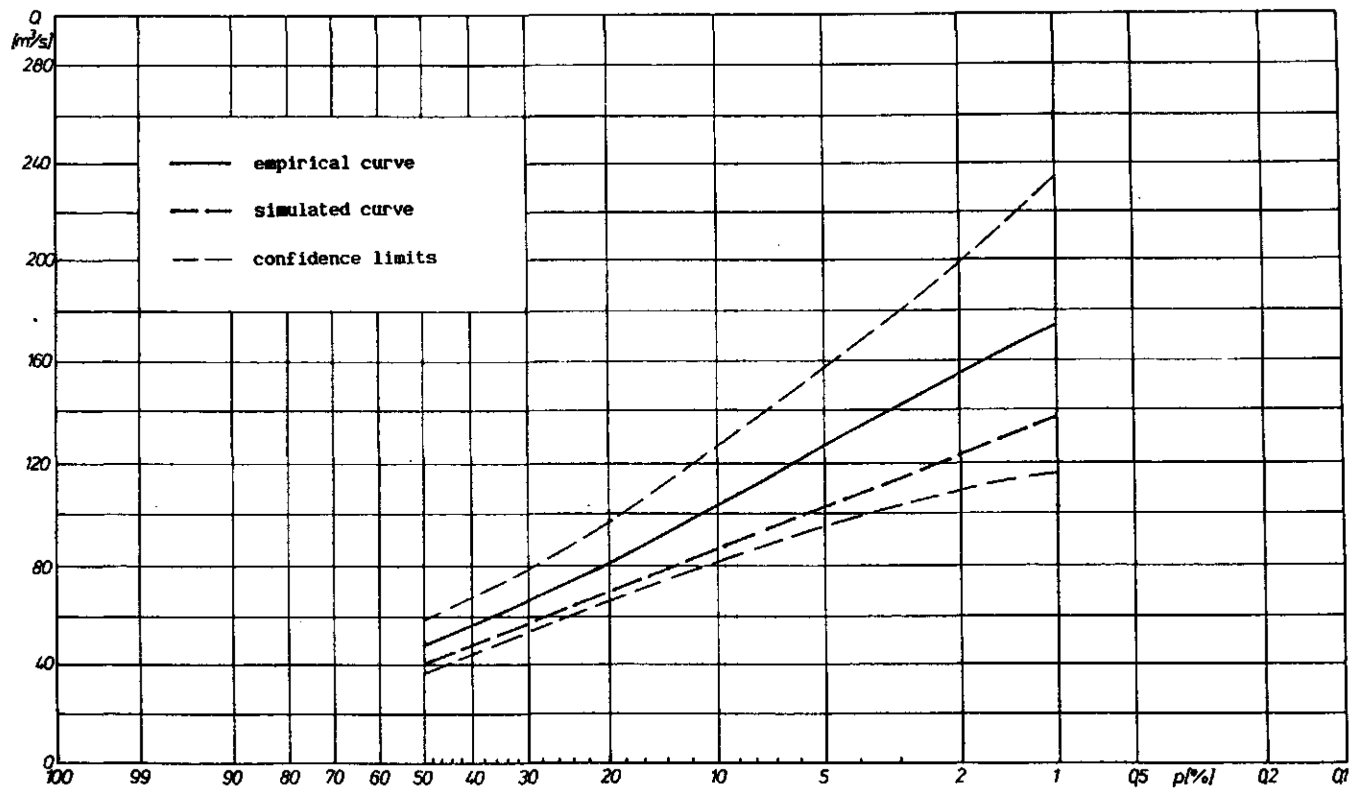

Figure 6. Comparison of probability curves for river Mszanka profile Mszana Dolna

with confidence limits for a confidence level equal to 0.84. The Kolmogorow-Smirnow test gave satisfactionary results for all cases.

Next, the probability curves were estimated again with the use of the developed procedure, and displayed on figures 3 to 6 for comparison with the empirical ones. The best agreement of empirical and simulated probability curves was achieved for the river Wisła (fig. 5), the worst for Leśnianka river, (fig. 3) where most of the simulated curve falls outside the confidence limits. There wasn't reasonable explanation found for this discrepancy.

Table 3. Watershed description summary for model evaluation

No	Watershed	Profile	Area [km^2]	Chanel length [km]	Slope [-]	Forest [%]
1	Leśnianka	Lipowa	21.5	6.2	0.101	96
2	Lubieńka	Lubień	46.9	11.1	0.032	42
3	Wisła	Wisła	54.0	12.8	0.058	75
4	Mszanka	Mszana Dolna	166.3	16.2	0.057	45

3.3. SENSITIVITY ANALYSIS

The influence on flood flow magnitudes by arbitrary changes in parameter values has been investigated in order to evaluate the model sensitivity. Three essential input characteristics have been tested: channel slope (I), annual rainfall total (P), and the CN parameter of the SCS method. Parameter values have been changed by increasing and decreasing parameter values with 50%, 20%, 15%, and 10%. Such an analysis was aimed to assess how far the parameter value errors influence flood flows. The second purpose was to assess, whether the model was flexible enough to reflect the influence of possible anthropogenic changes on flood flows.

The sensitivity analysis was carried out on the Wisła river catchment, which had shown the best agreement of empirical and simulated

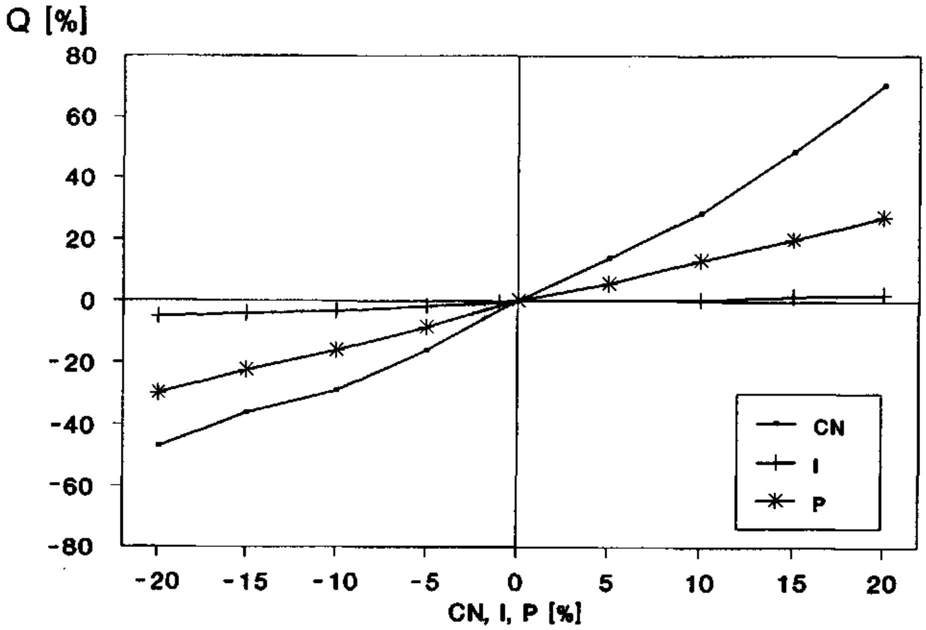

Figure 7. Results of sensitivity analysis for Wisla river

flow probability curves. The analysis was performed for flows with an assumed probability of 1%. The results of the investigation are shown in figure 7. The changes in channel slope show little influence on peak flow magnitude. The model is more sensitive to annual rainfall totals and is very sensitive to changes in CN parameter values. This analysis shows importance of accurate evaluation of CN parameter value and satisfactory flexibility of the model to reflect the influence of possible anthropogenic changes in the watershed on flood flows.

3.4. SIMULATION EVALUATION OF PROBABILITY CURVES FOR ANTHROPOGENIC CHANGES

Human activity causes a variety of changes in watersheds and their environment and influences the flow regime. Among others, changes connected with urbanization, deforestation and modification of agricultural structure are most often observed. There were two cases analyzed for the Wisła river: changes in forest quality (the catchment is for 75% covered by forest), and changes due to predicted climate changes caused by the increase of CO_2 and other radiative trace gases in the atmosphere.

Changes in forest covering is a very important factor in flood development. Although rational natural resources management in mountain areas will recommend to keep a forest cover, predicted changes consist of deterioration of the forest cover caused by acid rain. Four different forest density levels were chosen for the assessment of the impact of the predicted changes. It was dealt with by modifying the CN parameter value in the effective rain determination method. Partly damaged forest was taken to be the actual condition. The average value of the CN parameter for this case was 83.2. The CN parameter values for heavily damaged forest, average density and dense forest were calculated according to the SCS method and are given in Table 4. The probability curves for these three variants were calculated and they are shown in figure 8. The numbers describing particular curves together with the CN parameter values for different forest densities and averages for the watershed are shown in Table 4.

As expected, the probability curves have been moved towards higher values for lower forest densities. The differences were bigger for the lower probabilities.

Table 4. CN parameter values for different forest densities

Curve number	Forest density	Forest CN	Average CN
1	actual	81	83.2
2	damaged	83	84.7
3	average	79	81.7
4	dense	77	80.2

Published forecasts concerning the influences of CO_2 concentration increase on climate factors announce, that the resulting increase in air temperature would cause an increase in evapotranspiration and rainfall, speeding up hydrologic processes (Mimikou et al 1991). The so-called

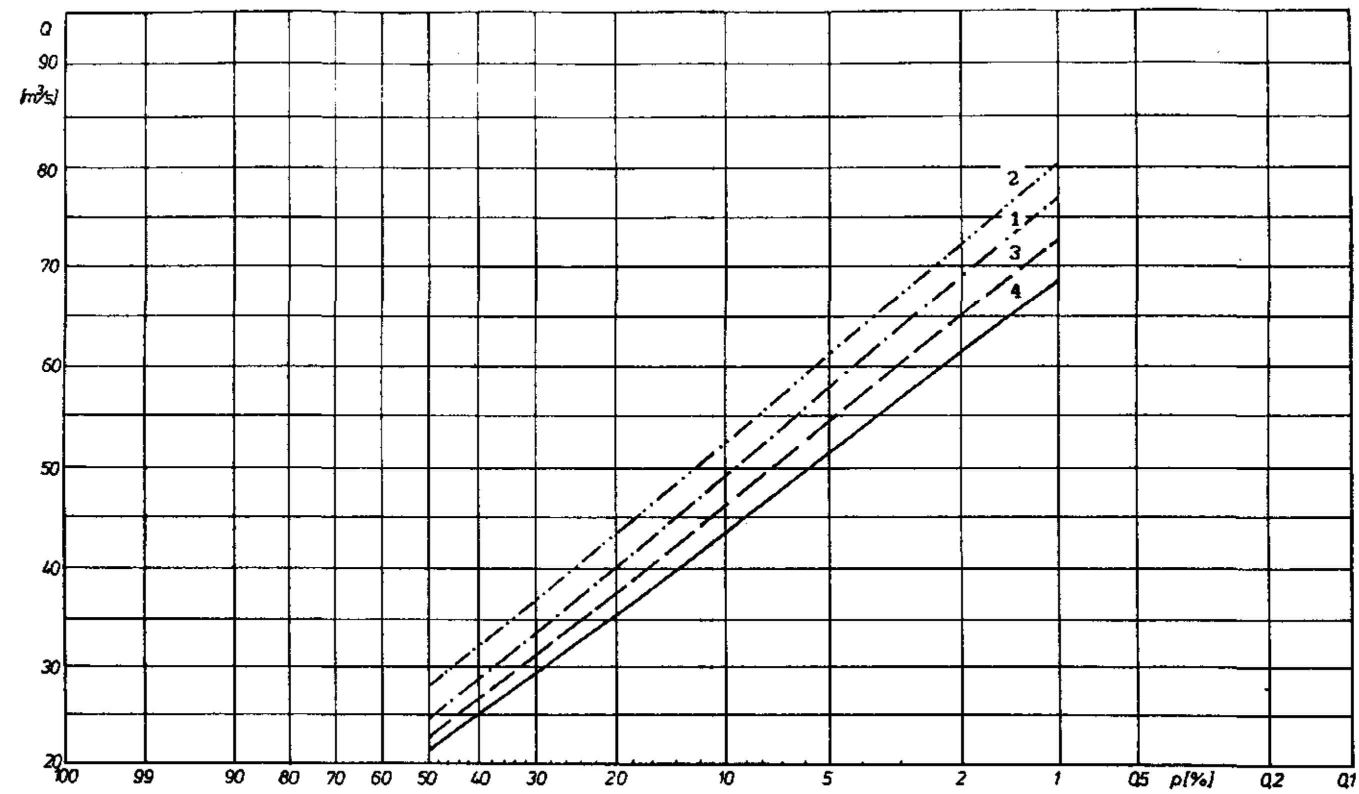

Figure 8. Probability curves comparison for different forest density

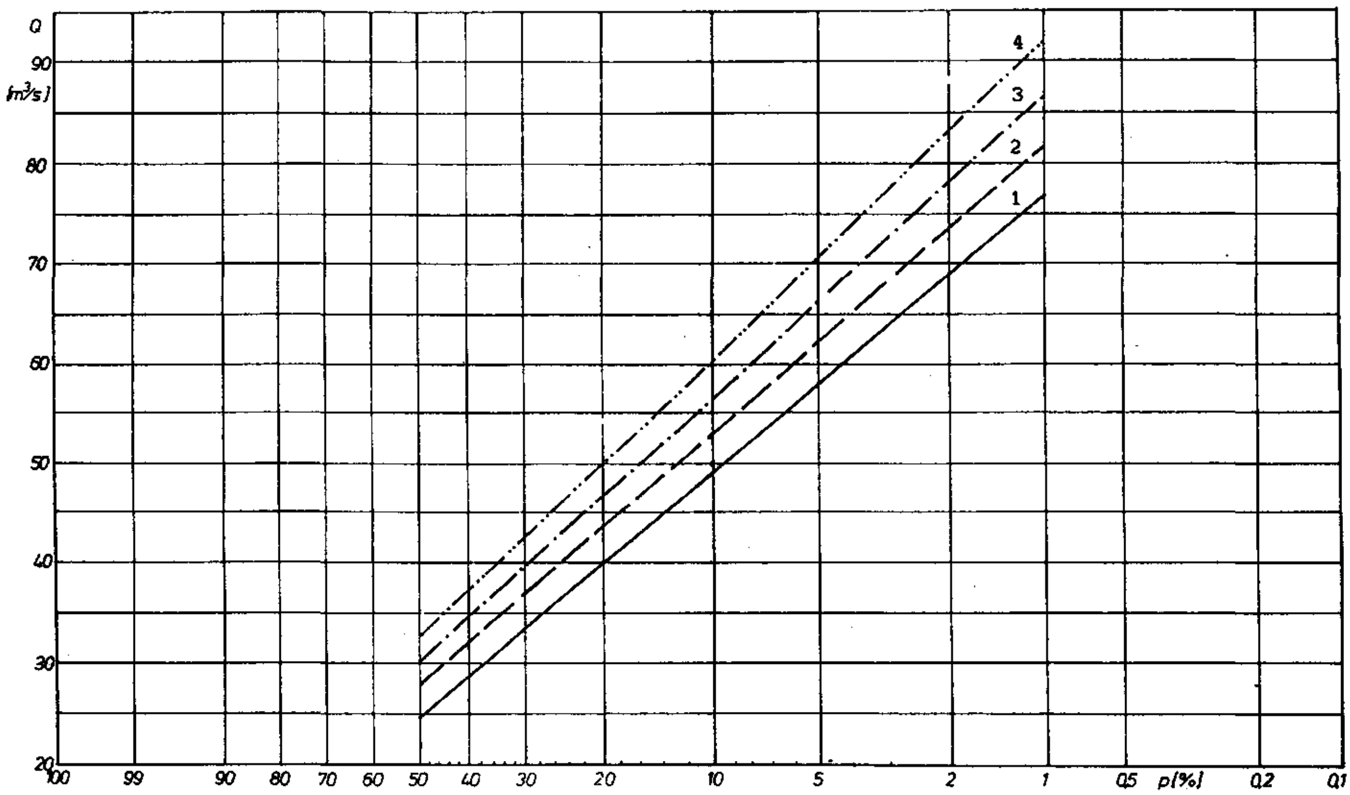

Figure 9. Probability curves comparison for different annual precipitation

General Circulation Models (Wilson, Mitchell 1987) are used for climate phenomena modeling. The most often made assumption is to double the atmospheric CO_2, and it results in an annual precipitation increase from 5% to 20% (Arnel, Reynard 1983).

Taking these results into account, three annual precipitation change scenarios were chosen for simulation computations: 5%, 10% and 15% increase in the annual precipitation totals. The event rainfall depths were assumend to increase with these same percentage like annual totals. Three probability curves were calculated, they are shown in figure 9, together with the actual one. These curves describe:

1 - actual curve,

2 - precipitation increase of 5%,

3 - precipitation increase of 10%,

4 - precipitation increase of 15%.

3.5. CONCLUSIONS

The proposed model for probability curves of flood flow computations aims on evaluating the probable flows for design purposes in ungauged watersheds with the rainfall data from nearby standard weather stations.

Verification computations for the sub-models of the proposed procedure have shown satisfactory results in comparison with empirical data. The developed model was tested with the use of empirically obtained probability curves for four small watersheds in the Carpatian Mountains and it has shown to be acceptable. Sensitivity analysis has shown that the model is able to reflect influences of man made changes on flood flow magnitudes by modifying the appropriate parameters.

Two cases of changes caused by human activity were further evaluated with the model for the Wisła river. It concerns changes in forest cover quality and increase of annual precipitation due to the increase of CO_2 in the atmosphere. The model has shown its usefulness for the described circumstances. Further investigations are recommended for model verification in a greater number of watersheds, and for sub-model refinements.

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