

DETERMINATION OF SCS-CN INITIAL ABSTRACTION RATIO IN A CATCHMENT PRONE TO FLASH FLOODS

¹Martin CALETKA*, ²Monika ŠULC MICHALKOVÁ

^{1,2}Department of Geography, Faculty of Science, Masaryk University, Kotlářská 2
611 37 Brno, Czech Republic, e-mail: ¹martin.caletka@mail.muni.cz, ²sulc@mail.muni.cz

¹T. G. Masaryk Water Research Institute, Brno Branch, Mojžířovo náměstí 16
612 00 Brno, Czech Republic, e-mail: martin.caletka@vuv.cz

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Abstract: The soil conservation service - curve number method is a globally used approach to simulations of surface runoff for its simplicity and applicability. Nevertheless, relevant simulations require proper setting of the model's components. This work focuses on optimization of initial abstraction ratio λ in the Husí potok sub-catchments in Czech Republic. Due to favorable morphology, the watershed is prone to flash floods and accurate modeling of surface runoff is of high interest. The analysis was conducted using pairs of discharge and rainfall measurements. The results outline that the traditional value $\lambda=0.2$ is too high in this watershed and should be reduced.

Keywords: Curve number, Flash flood, Initial abstraction ratio, Surface runoff

1. Introduction

Despite the increasing potential of hydrological models, the nature of some hydrological-meteorological phenomena burdens the modeling approaches by uncertainties, resulting in limited accuracy and predictability of the outputs. Specifically, surface runoff induced by intense rainfall belongs to such phenomena [1], [2], thus posing a challenging task.

One of the frequently used approaches to simulating surface runoff is the Soil Conservation Service - Curve Number method SCS-CN [3]. Originally, the method was developed to estimate surface direct runoff in various small watersheds in the USA. During the decades, the method has been incorporated into many hydrological models,

* Corresponding Author

e.g. [4]-[7], sediment yield, e.g. [8], [9], water quality modeling, e.g. [10]-[13], or water harvesting, e.g. [14]-[16].

The SCS-CN method has been an object to many expert discussions as it contains several shortcomings and inconsistencies, for example the absence of rainfall intensity and storm duration, unrealistic distribution of Curve Number (CN), limited flexibility of the Antecedent Moisture Conditions (AMC) display and fixing of the initial abstraction, resp. initial abstraction ratio, e.g. [17]-[24], to eliminate the existing problematic aspects of the procedure.

The initial abstraction ratio is usually set to 0.2 based on the data from North-American watersheds and has been discussed in many studies in terms of its validity and applicability in different geographical conditions, e.g. [7], [19], [25]. It was examined that the $Ia-S$ relationship incorporating the AMC based on the previous rainfall amount can improve the runoff estimation [8]. Similarly, a new non-linear $Ia-S$ relationship arising from the antecedent storm precipitation and S was introduced [26].

For this research, a catchment prone to flash floods was chosen. Severe flash flood events were recorded in this catchment in summer 2009 and 2010 [27], [28]. These events encouraged the authors to focus on this specific area and launch measurements of precipitation and water levels so that rainfall-runoff events can be recorded and assessed. Specifically, the objectives of this study are:

- i) to present the preliminary results of the analysis on identification of the appropriate initial abstraction ratio λ values in different catchments;
- ii) to compare whether the λ vary in different sub-catchments and discuss possible reasons.

2. Study area

The study was conducted in three sub-catchments (A, B, C) of the Husí potok catchment (49°80'N - 49°67'N, 18°01'E - 17°78'E) in the north-east of the Czech Republic. The Husí potok brook is a left-side tributary of the Oder River and covers an area of 142 km². The watershed's upper part is located on the easternmost edge of the Bohemian Massif and the lower parts of the area belong to the Subcarpathia - depression area along the outer base of the Carpathian arc. Majority of the upper parts of the catchment have a flat relief, which gradually passes into relatively narrow valleys with greater longitudinal slope. The valleys widen downstream and turn to a slightly curved or flat relief. Elevations within the watershed range from 282 m to 563 m. The slopes range from 0 ° to 59 °, with the average of 6 °. The length of the main channel is 26.7 km. The streams form a dendritic drainage system. The mean annual runoff height at the outlet is 156 mm. The annual precipitation is approximately 650 mm, of which over 70% is normally recorded between April and September. Two main soil types occur in the study area, namely cambisols, found in the upper parts of the watershed, and luvisols covering mostly the lower parts. On the flat plateau, stagnosols can be found as well. There is a characteristic distribution of land use categories in the study area. A portion of the upper parts of the watershed is covered by arable land. Large blocks of arable land also prevail in the lower parts. Forests and meadows are mostly

concentrated in the sloping transition between the upper and lower parts of the watershed and in the valleys. The percentages of individual land use categories for each sub-catchment are detailed in *Table I*. The specific arrangement of the relief and the great portion of arable land on the upper plateau pose a favorable prerequisite for generation of concentrated surface runoff when intense rainfall occurs.

Table I

Percentage of land use categories in the experimental sub-catchments (1 - arable land; 2 – meadows; 3 - arable land with scattered vegetation; 4 - alternating forests and shrubbery; 5 - mixed coniferous forest; 6 - coniferous forest; 7 - scattered built-up area; 8 - industrial zones).

sub-catchment	percentage of land use category							
	1	2	3	4	5	6	7	8
A (57.8 km ²)	51.5	8.6	9.8	3.3	5.1	15.6	6.0	0.2
B (20.2 km ²)	47.5	6.1	7.5	9.0	5.5	19.0	5.3	0.0
C (5.9 km ²)	53.5	2.6	9.8	5.4	5.4	15.9	2.2	0.0

3. Materials and methods

3.1. Data collection

The Husí potok catchment is covered by network of 17 automatic rain gauges providing hourly rainfall data. Every hour, mean precipitation is calculated using the measurements at all rain gauges by means of Thiessen polygon interpolation procedure [29] (*Fig. 1*). The mean rainfall is calculated as weighted arithmetic mean where the weights are the areas of polygons or their parts in the watershed. In the event of any device failure, the deployment of the rain gauges allows to replace the missing measurement by data from another device. Thus, the distribution of Thiessen polygons was changing correspondingly.

During the period April-September 2008-2016, the total of 1292 rainfall events were recorded in the Husí potok catchment. The number of analyzed rainfall-runoff events is considerably lower compared to the total of the events as only events with well pronounced runoff (hydrograph) without any influence of previous events (i.e. without compound hydrographs) were selected. In total, 80 events were analyzed in catchment A, 26 events in catchment B and 20 events in catchment C.

Data from 3 level gauges (profiles A-C) were used (*Fig. 1*). Profile A is located on the main stream the Husí potok brook and has level data for the period 2008-2016. Profiles B and C monitored minor tributaries and had only measurements for period 2016-2017 available. The catchment C is a sub-catchment of the catchment B. In order to transform the water level series to hydrographs, rating curves were calculated for the profiles based on hydrometric measurements, leveling and by means of Chézy formula. The principle of the calculation resides in the relationship between actual discharge and water level, morphometric characteristics of the channel and Manning's roughness coefficients [30] both of the channel bed and the banks.

Base flow separation was carried out according to the methodology used at the Czech Hydrometeorological Institute [31]. An example of the total discharge and the separated base flow in the profile A is presented in Fig. 2.

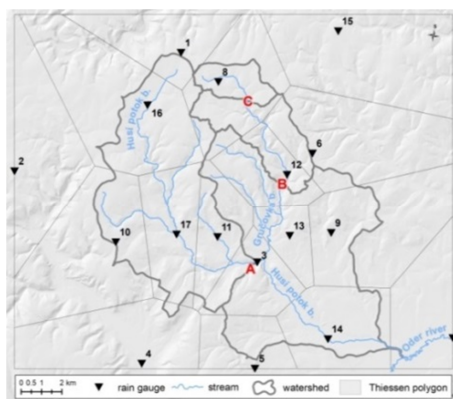


Fig. 1. Deployment of level gauges and rain gauges with delimitation of Thiessen polygons in the Husí potok catchment and its sub-catchments

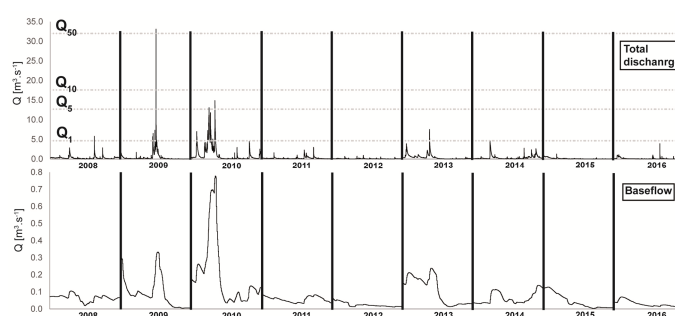


Fig. 2. Total discharge and base-flow in profile A in period IV-IX 2008-2016

3.2. SCS-CN method

The original SCS-CN method is a lumped rainfall-runoff model. The procedure is based on combination of the water balance equation

$$P = Ia + F + Q, \quad (1)$$

and two fundamental assumptions

$$Q/(P - Ia) = F/S, \quad (2)$$

$$Ia = \lambda S, \quad (3)$$

where Q is the direct runoff (mm); P is the precipitation (mm); Ia is the initial abstraction (mm); F is the cumulative infiltration (mm) not including Ia ; S is the

maximum potential retention (mm) after the start of the runoff and λ is the initial abstraction ratio (dimensionless).

Using Eqs. (1), (2) and (3), the runoff Q can be expressed as

$$Q = (P - Ia)^2 / (P + S - Ia), \quad \text{for } P \geq Ia, \\ Q = 0, \quad \text{for } P < Ia. \quad (4)$$

The maximum potential retention S is expressed by formula

$$S = 25400 / CN - 254, \quad (5)$$

in which the CN represents the curve number that is based on the hydrologic soil group, land cover and 3 degrees of the AMC given by the 5-day precipitation sum P_{5d} (mm) prior to each rainfall event. In the Czech Republic, the AMC degrees are delimited by the ranges of $P_{5d} < 0; 36$) - dry conditions (CN_I), $< 36; 53$) - normal conditions (CN_{II}), $< 53; \infty$) - wet conditions (CN_{III}).

The λ is usually set to 0.2. However, plenty studies were dealing with the applicability and relevance of this Ia - S relationship with intention to better represent the local conditions.

3.3. Event analysis

For the determination of λ values, suitable rainfall-runoff events were chosen. Unlike other studies, e.g. [25], no criteria for the rainfall-runoff events regarding the continuous rainfall, peak discharge and antecedent runoff conditions were applied in this research. Since the afore-mentioned requirements do not reflect most real rainfall-runoff events in these particular geographic conditions, only the criterion of well pronounced wave in the hydrograph was applied. In order to exclude rainfall events causing compound hydrographs, ample interval between the rainfall events was required.

The determination of λ values for each rainfall-runoff event was as follows:

1. Rainfall event was chosen;
2. The corresponding hydrograph was delimited;
3. Direct runoff was calculated as the total direct runoff volume divided by the area of a watershed;
4. Based on the synchronized break-point records of the rainfall and runoff height, the initial abstraction Ia was calculated as the rainfall height at the moment when the direct runoff begins;
5. Using the known values of P , Q and Ia for each event, the maximal potential retention of the watershed S was calculated through the Eq. (6);
6. Finally, the initial abstraction ratio was calculated by dividing Ia by S .

In watershed A, a total of 80 rainfall events were chosen from the period 2008-2016 for the determination of λ ratio values. In the other 2 watersheds, discharge data (level data, respectively) was collected in period 2016-2018, thus having less number of

rainfall-runoff events to be analyzed (26 events in catchment B, 20 events in catchment C).

3.4. Comparing the estimated runoff

According to [32], the maximum potential retention S can be written as:

$$S = \left(2\lambda P + (1 - \lambda)Q - \left((2\lambda P + (1 - \lambda)Q)^2 - 4\lambda^2(P^2 - QP) \right)^{0.5} \right) / (2\lambda^2). \quad (6)$$

For each event, the traditional λ value is substituted in the Eq. (6) to obtain S . The arithmetic mean of S is then used in Eqs. (3) and (4) to calculate the runoff. The same procedure was applied using mean and median λ values for each watershed.

The quality of the estimated runoff heights was evaluated by means of Nash-Sutcliffe coefficient E [33], root mean square error $RMSE$, normalized root mean squared error $NRMSE$, bias e and coefficient of determination r^2 . The Nash-Sutcliffe coefficient E is given as:

$$E = 1 - \frac{\sum (Q_{predi} - Q_{obsi})^2}{\sum (Q_{obsi} - Q_{ave})^2}, \quad (7)$$

where Q_{predi} is the i -th observed runoff depth, Q_{predi} is the i -th predicted runoff depth and Q_{ave} is the mean observed runoff depth. The E can range from $-\infty$ to 1. Low E values indicate less accurate prediction, whereas E equal to 1 indicates a perfect match.

Root mean square error $RMSE$ is given as:

$$RMSE = \sqrt{\frac{\sum (Q_{predi} - Q_{obsi})^2}{n}}. \quad (8)$$

Normalized root mean square error $NRMSE$ is defined as:

$$NRMSE = RMSE / Q_{ave}. \quad (9)$$

Good performance of the model is indicated by lower values of both $RMSE$ and $NRMSE$. The bias e is given as:

$$e = \frac{\sum (Q_{predi} - Q_{obsi})}{n} \quad (10)$$

and expresses the average difference between the predicted and observed values of runoff depths.

3.5. Model fitting

Model fitting resides in the iterative least squares procedure, searching for a pair of λ and S so that the sum of the squared difference between the runoff observed and modeled

$$\sum \left(Q - (P - \lambda S)^2 / (P + (1 - \lambda)S) \right)^2 \quad (11)$$

is a minimum. Only a single value of both λ and S for the entire dataset is identified. The iterative calculation was carried out using the Python programming language.

3. Results

The initial abstraction ratio λ values considerably differ among the sub-watersheds, as well as between the events (see *Fig. 3a*). In catchment A, the λ ranged from 0.0005 to 0.577, with a mean value of 0.115 and a median of 0.039. More than 80% of the rainfall-runoff events had λ value less than 0.200, indicating that the original value 0.200 is too high in this particular catchment.

In the neighboring catchments B and C, the λ values appear to be even lower. In catchment B, the array of λ has the minimum 0.0001, the maximum 0.275, the mean 0.037 and the median 0.0077 (*Fig. 3b*). The catchment C has the λ ranging from 0.0004 to 0.0907, with a mean 0.021 and a median 0.015 (*Fig. 3c*). It should be noted, however, that the number of rainfall-runoff event is much lower than in the catchment A (20 events in catchment B, 26 events in catchment C) due to shorter monitoring time.

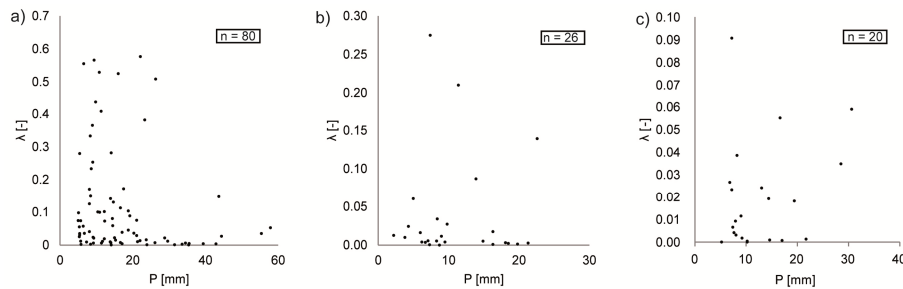


Fig. 3. Initial abstraction ratio λ versus rainfall depth P for each rainfall-runoff event in catchment a) A; b) B and c) C

Lower λ values in catchments B and C are probably caused by presence of series of ponds in the upper part of the watershed (especially in catchment C). When a rainfall event occurs, the ponds are able to capture or slow down a certain portion of the surface runoff, resulting in a decreased volume of the direct runoff passing through the outlet. Due to low Q , the transformed Eq. (4) provides high values of S which are compensated by low λ values.

Based on the above-mentioned findings, the runoff heights were recalculated for all catchments using the mean and median λ values. Moreover, λ values providing the runoffs with the highest E were identified (best E). The predicted Q was then evaluated by the criteria (7)-(10) overviewed in *Table II*. It is apparent that the modified λ values lead to overall enhanced results as the E increases and both $RMSE$ and $NRMSE$ decrease in all cases.

A paired Student t-test revealed that in catchment A (*Fig. 4*), there are significant differences between the Q computed using reduced λ values and those using $\lambda = 0.200$ at a significance level of 0.01. However, in the other two catchments, the t-test did not

prove any significant differences. This can be attributed to the lower number of events and the specific runoff conditions in catchments B (Fig. 5) and C (Fig. 6).

Table II

Statistics for different λ values in catchments A, B and C

catchment		λ	E	RMSE mm	NRMSE [-]	e [mm]	r^2
A	traditional	0.200	-0.265	5.40	1.16	-0.26	0.39
	mean	0.115	-0.053	4.92	1.06	-0.62	0.39
	median	0.039	0.166	4.38	0.94	-1.22	0.40
	best E	0.001	0.218	4.25	0.91	-1.95	0.40
B	traditional	0.200	-5.547	1.30	3.32	0.49	0.56
	mean	0.037	0.092	0.18	0.46	0.09	0.57
	median	0.008	0.532	0.09	0.24	-0.08	0.57
	best E	0.010	0.536	0.09	0.24	-0.06	0.57
C	traditional	0.200	-42.500	2.68	11.77	0.62	0.29
	mean	0.021	-2.092	0.19	0.08	0.08	0.31
	median	0.015	-1.218	0.14	0.60	0.05	0.31
	best E	0.001	0.209	0.05	0.21	-0.07	0.32

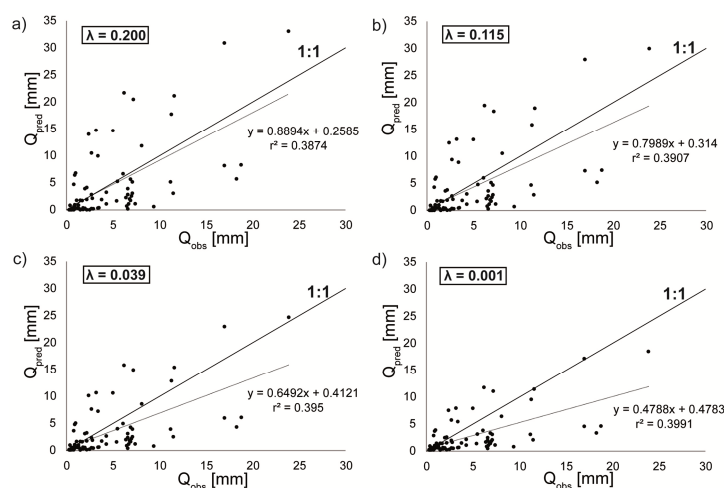


Fig. 4. Observed versus estimated runoff depth for the λ values a) 0.200; b) 0.115; c) 0.039; d) 0.001 in catchment A

The rainfall and runoff data was also fitted to the general runoff equation by least squares using an iterative computation to identify the corresponding values of λ and S (CN, respectively). The results are provided in Table III. Notably, the difference between catchment A and the other two is noteworthy. Most probably, the presence of the ponds is manifested by considerably greater values of S , especially in catchment C where the influence of the ponds on the direct runoff appears to be particularly high. An example of the recalculation of the observed runoff heights on the basis of the best fit S and λ values is provided in Fig. 7.

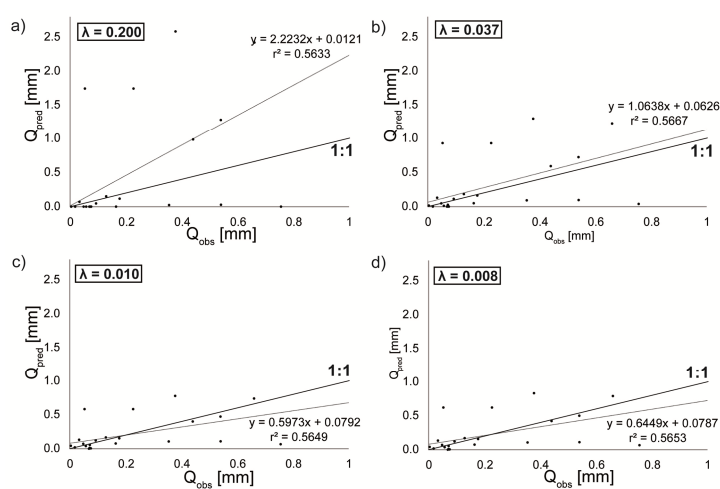


Fig. 5. Observed versus estimated runoff depth for the λ values a) 0.200; b) 0.021; c) 0.015; d) 0.001 in catchment B

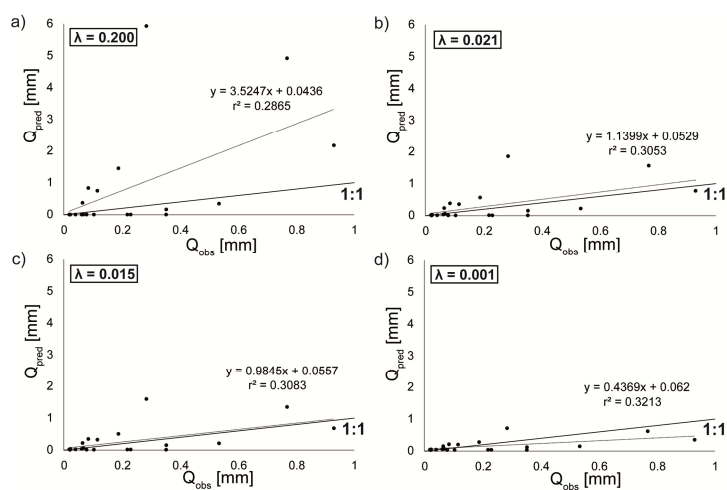


Fig. 6. Observed versus estimated runoff depth for the λ values a) 0.200; b) 0.037; c) 0.008; d) 0.010 in catchment C

Table III

Summary of λ and S values from model fitting in the experimental catchments

Catchment	λ [-]	S [mm]	CN [-]
A	0.0	102.2	71.3
B	0.0	388.7	39.5
C	0.0	1267.7	16.7

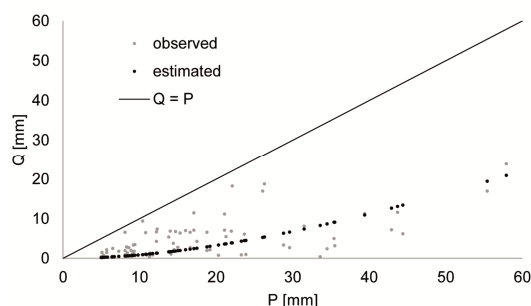


Fig. 7. Comparison of the observed and recalculated rainfall-runoff events using the S and λ values identified by the model fitting procedure in catchment A

4. Conclusions

In this study, the SCS-CN initial abstraction ratio λ in the Husí potok catchment was determined by analyzing real rainfall and runoff data. Similarly to other studies that identified value of $\lambda = 0.05$ as more representative, the conclusion of this research is that the traditionally used value $\lambda = 0.200$ is too high in this particular experimental area. The study was carried out in three catchments in order to compare the local specificities. In the largest one (catchment A), mean λ is 0.115 and median 0.0039. In smaller catchment B, mean λ is 0.037 and median 0.008. In catchment C, that is actually a sub-catchment of catchment B, mean λ is 0.021 and median 0.015. The analysis has shown that incorporating lower λ values leads to statistically better results in catchment A. In the other two, the modified λ did not provide statistically significant enhancement of the modeled runoff heights. Nevertheless, the findings of this study indicate that adjustment of λ should be taken into consideration and reduced values should be used in catchments similar to those presented here.

Another aspect that should be noted is the gauging interval of the data used in this study. Hourly interval of both the rainfall and water levels may lead to biased results due to inaccurate identification of the inflection points in the hydrograph and recognition of the time between the beginning of a rain event and the moment when direct runoff begins. This aspect is limiting for accurate determination of initial abstraction I_a as well as runoff height Q , which are important especially in case of short rainfall events with great rain intensity during the initial part of the events. As a result of longer gauging interval, relatively low values of the r^2 for all modifications of the λ in all catchments were recorded.

Assuming that the λ values differ both between catchments and individual rainfall runoff events, the determination of appropriate values must be based on analyzing representative training datasets of rainfall-runoff events in each catchment rather than using a fixed universal value of λ . At the same time, data with shorter gauging intervals should be used, permitting more precise delimitation of the inflection points in hydrographs. The subsequent research will be focused on analyzing greater array of rainfall and runoff data from various experimental catchments and application in modeling of direct runoff by means of HEC-HMS.

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