Numerical Study on the Impact of Revising the Rainstorm Intensity Formula on the Storm Flood Disaster Prediction in Huinan, Pudong District

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Abstract: The numerical model by MIKE FLOOD software has been set up with coupled the rainfall runoff sub-model and underground network sub-model by MIKE URBAN software and the overland flow sub-model by MIKE 21 software to simulate the storm flood in Huinan, Pudong District. After the calibration and validation, the model is applied to study the impact of revising the rainstorm intensity formula on the local storm flood disaster prediction. And the conclusions are obtained: after the formula revised, the time to appear the maximum waterlogging area would be delayed, and the local storm flood disaster would worsen under the current drainage pipe networks, i.e., the overland flood range and its depth would slightly increase.
Keywords: storm flood; disaster; rainstorm intensity formula; waterlogging; numerical simulation

1. Introduction

The torrential rain has the characteristic of the high intensity and large amount rainfall for the higher water level. When the rainfall exceeds the capacity of the urban drainage system, it is easy for the local ground to be waterlogged due to all the rainwater is not drained quickly and efficiently, and then the urban flooding will occur with the low-lying houses got drowned, the local traffic crippled, which strongly affect the people's life and work. A few mathematical models have been established to study the urban flooding, e.g. InfoWorks CS[1-2] , Storm Water Management Model (SWMM)[3], GIS-based urban flood inundation model[4], 2D hydrodynamic model capable of simulating flash floods[5], MOUSE model[6-8].

Rainstorm intensity formula is one of the basic methods for the design of municipal facilities and drainage networks. And the designed pattern has a fundamental role not only to unify the computing standards but also to guarantee facility.

Recently, more and more extreme rainstorms in Shanghai city have become stronger and stronger. The storm intensity formula generated in 1960s cannot be available to the current rainstorm characteristics and rainfall patterns, which is not conducive not only to the design and optimum construction of the municipal facilities, but also to the elimination of urban rainfall flood disaster. It needs to revise the local storm intensity formula. So, the standard of rainstorm intensity formula and design rainstorm distribution in Shanghai city (DB 31/T 1043-2017)[9] was officially released on March 3rd, 2017.

Huinan, located in the south of Pudong District in Shanghai, has been suffered by the storm flood disasters for years. Therefore, the model coupled with the rainfall runoff sub-model and the underground network sub-model by MIKE URBAN, and the overland flow sub-model by MIKE 21 are established in MIKE FLOOD platform to simulate the storm flood in this research, and the impact of revising the rainstorm intensity formula on the storm flood disaster prediction in the local region is studied.

2. Local rainfall characteristics

There is a tropical East Asian mon-soon, and the oceanic climate with plenty of rains in Huinan. And Pudong Canal, Zhonggang River, Yaogou River and Sanzaolu River are around it (see Fig. 1), with the normal water level of 2.50 ~ 2.80 m. When the storm flood disaster occurs in Huinan, there are many houses, factories and croplands often suffered, especially, the region, east to Yaogou River, south to Zhonggang River, west to Pudong Canal, and north to Sanzaolu River (see Fig. 1).

According to the analysis of the meteorological data at Huinan Hydrographic Station from 2009 to 2014, the local short-duration rainfall is strong, and trends up, especially since 2011 (see Fig.2). In general, the number of the flood disasters is positively correlated with the annual precipitation, i.e., the more rainfall is, the easier the disaster appears (see Fig.3). Furthermore, the rainstorm often occurs during June to August every year (see Table 1).

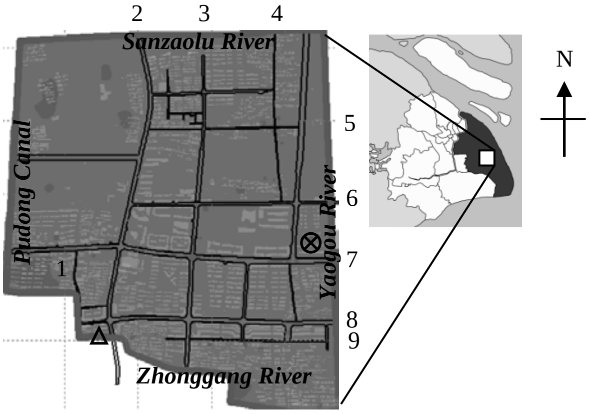


Fig.1 Location of Huinan in Pudong District ("Δ" and "⊗" show Huinan Hydrographic Station and Gongji Road Rain Pump. Numbers "1" ~ "9" show Meihua Road, Nanzhu Road, Jinhai Road, Chuannanfeng Road, Tanghong Road, Gongbei Road, Gongji Road, East Renmin Road and Huayuan Road.)

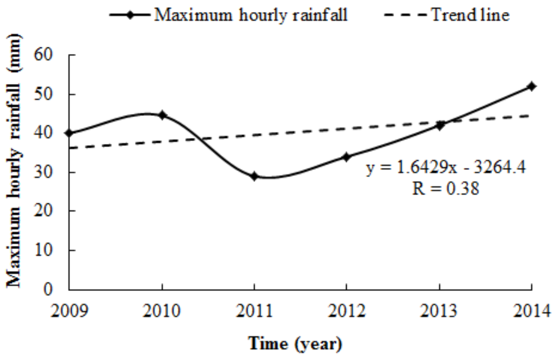


Fig.2 The trend for the maximum hourly rainfall in Huinan during 2009 to 2014

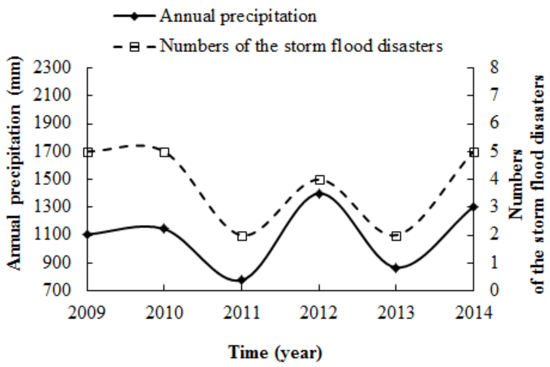


Fig.3 Relationship between the annual precipitation and numbers of the storm flood disasters in Huinan during 2009 to 2014

Table 1 Statistics of the rainstorms in each month in Huinan during 2009 to 2014

Daily rainfall (mm) \ Time	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sep.	Oct.	Nov.	Dec.
Rainstorm (50 ~ 100)	0	0	0	0	0	4	3	4	1	1	1	0
Strong rainstorm (100 ~ 250)	0	0	0	0	0	1	0	1	0	1	0	0
Extreme rainstorm (> 250)	0	0	0	0	0	0	0	0	0	0	0	0
Total	0	0	0	0	0	5	3	5	1	2	1	0

3. Model set up

3.1 Control equations

The runoff in the rain inlet can be calculated by[6]

$$Q = q\psi F \tag{1}$$

where Q represents the runoff in the rain inlet; q is the designed rainfall intensity; ψ is the coefficient of the rainfall runoff; F is the catchment area.

The surface runoff can be calculated by[6]

$$W = W_1 + W_2 + W_3 = HS_1 + HS_2 - Q_x + HS_3 - Q_t = qtS_1 + qtS_2 - \sum_{i=1}^{m} Q_i + qtS_2 - 60\, fS_3 t \tag{2}$$

where W is the surface runoff; W_1 is the runoff of the impervious zone without the depression storage; W_2 is the runoff of the impervious zone with the depression storage; W_3 is the runoff of the pervious zone; H is the total rainfall; S_1 is the area of the impervious zone without the depression storage; S_2 is the area of the impervious zone with the depression storage; S_3 is the area of the pervious zone; Q_x is the infiltration of the impervious zone with the depression storage; Q_t is the infiltration of the pervious zone; Q_i is the depression storage capacity of the i^{th} hollow, $Q_i = 1.49L_i\ (H - h_{pi})^{5/3}S_{0i}^{0.5}/n$, where L_i is its length, h_{pi} is its water depth, S_{0i} is its slope, n is the roughness; f is the infiltration rate, $f = f_c + (f_0 - f_c)e^{-ktm} = f_0(1 - W / W_m) + f_c\ W / W_m$, where f_0 is the initial maximum infiltration rate, f_c is the minimum infiltration rate, k is the attenuation coefficient, t_m is the time of the saturated soil changing to be the dry soil, W is the soil moisture content, and W_m is the soil retention.

The discharge of the pipe line can be calculated by[6]

$$\begin{cases} \dfrac{\partial A}{\partial t} + \dfrac{\partial Q'}{\partial x} = 0 \\ \dfrac{\partial Q'}{\partial t} + \dfrac{\partial}{\partial x}\left(\dfrac{Q'^2}{A}\right) + gA\dfrac{\partial h}{\partial x} + gAS_f + gAh_L = 0 \end{cases} \tag{3}$$

where A is the cross-sectional area of the pipe line, Q' is the discharge of the pipe line, h is the water head, S_f is the frictional resistance of the slope, $S_f = n^2\ Q'\ |v|\ /\ (AR^{4/3})$, where v is the velocity, R is the hydraulic radius, and h_L is the water head loss.

When the hollow has the storage function, its discharge can be calculated by[6]

$$\frac{\partial h'}{\partial t} = \frac{\sum Q'_t}{S_t} \tag{4}$$

where h' is the water head of the hollow, Q'_t is the discharge of the hollow, S_t is the water area of the hollow. But when the hollow has the only connect function, its discharge is calculated by $\Sigma\ Q'_t = 0$.

3.2 Computational grids

The research region is east to Yaogou River, south to Zhonggang River, west to Pudong Canal, and north to Sanzaolu River, about 5 km^2, including Huinan Station of Metro Line 16 and the core zone of Dongcheng District (see Fig.1), with 642 hollows, 619 pipe lines, 22 outlets, 23.4 km of the total pipe lengths, where has divided to be 579 x 656 square grids with the uniform interval of 4 m. And 614 catchments in the study area has been generated with Thiessen Method with one water collection hollow in each catchment to make the rainfall runoff flow into the drainage pipes.

3.3 Boundary conditions

In this study, the river open boundaries are setup with the different water levels under the various short-duration rainstorms (see Table. 2), and the diverse rainfall is created to be the rainfall conditions before and after the local rainstorm intensity formula revised, i.e., the formula of $q = 1600\ (1 + 0.846\lg P)\ /\ (t + 7.0)^{0.656}$ (DB 31/T 1043-2017) [9] by the Chicago Rainfall Pattern with the rainfall peak coefficient of 0.405 is instead of $q = 5544\ (P^{0.3} - 0.42)\ /\ (t + 10 + 7\lg P)^{0.82 + 0.07\lg P}$[10] by the Chicago Rainfall Pattern with the rainfall peak coefficient of 0.3 in Shanghai, where P is the designed reoccurrence period, t is the rainfall duration.

The simulated region is mainly composed of buildings, roads, green fields and water. And the different impervious rates have been used, e.g. 90 % for buildings, 85 % for roads, 25 % for green fields, zero for water, 50 % for the rest.

Table 2 The rainfall and the river water levels under the different conditions

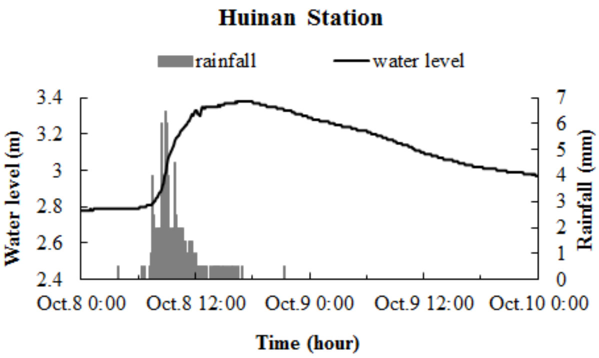
Designed reoccurrence period (year)	Total rainfall in 120 min (mm)		River water level (m)
	Original formula	Current formula	
Once every three years (P = 3 a)	62	68	2.85
Once every five years (P = 5 a)	70	76	2.90

3.4 Model input parameters

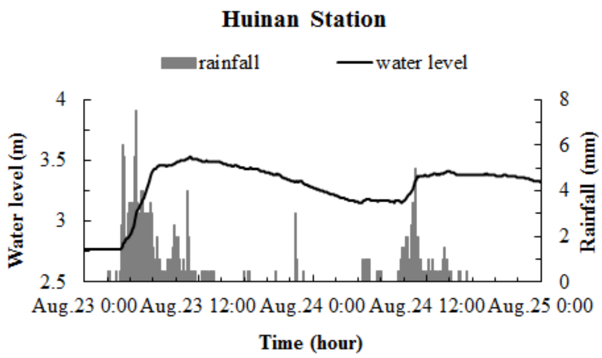
The mean surface flow velocity is adopted as 0.3 m/s, the hydraulic decay coefficient is 0.9, the initial abstraction is 0.0006 m, and the coefficient of the rainfall runoff is 0.6 in the rainfall runoff sub-model. The roughness of the concrete drainage pipe lines is used 0.0015 in the drainage hydrodynamic sub-model. The manning coefficient is 32.0, and the water depth of the dry grid is below 0.002 m while the water depth larger than 0.003 m is wet in the overland flood sub-model. And the time step is set to 1 s.

3.5 Model calibration and validation

The simulated results have been compared with the actual storm flood disaster in Huinan on Oct. 8th in 2013 and Aug. 23th in 2015 to calibrate and validate the model respectively. And the calibrated results show that the modeled overland flood distribution range and its depth are agreed with the actual situation (see Table 3), and the time to subside water costs about 16 hours from 10:00 on Oct. 8th to 1:25 on Oct. 9th in 2013 is also satisfied with the actual reports. After the validation, it shows that the modeled flood range and its depth are also conformed to the on-site situation, except for Gongji Road (Jinhai Road ~ Chuannanfeng Road), due to the road construction in 2015. So this model could be adopted to simulate the storm flood in Huinan, Pudong District.

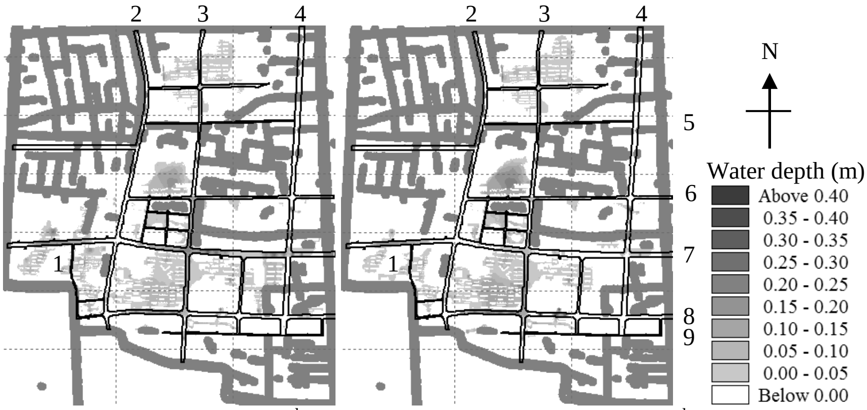


(a) from Oct. 8th to 10th in 2013



(b) from Aug. 23th to 25th in 2015

Fig.4 Temporal evolution of the observed rainfall and water level at Huinan Hydrographic Station



(a) at 10:00 A.M. on Oct. 8th, 2013 (b) at 7:00 A.M. on Aug. 23th, 2015

Fig.5 Layout of the simulated overland flood distribution in Huinan when the range is maximum (Numbers "1" ~ "9" show Meihua Road, Nanzhu Road, Jinhai Road, Chuannanfeng Road, Tanghong Road, Gongbei Road, Gongji Road, East Renmin Road and Huayuan Road)

Table 3 Comparisons of the simulated flood depth with the actual situation in Huinan, Pudong District

Time	Location	H_{max} (m) Actual Situation	H_{max} (m) Simulated Results
at 10:00 A.M. on Oct. 8th, 2013	Gongji Road	≈ 0.10	≈ 0.10
	East Renmin Road (Nanzhu Road ~ Jinhai Road)	≈ 0.15	≈ 0.15
	Jinhai Road (Gongbei Road ~ East Renmin Road)	≈ 0.20	≈ 0.20
	Jinhai Road (north of Gongle Road)	≈ 0.10	≈ 0.10
	Jindicheng Neighborhood	≈ 0.10	≈ 0.10
	Dongchenghuayuan II Neighborhood	≈ 0.05	≈ 0.05
at 7:00 A.M. on Aug. 23th, 2015	Gongji Road (Jinhai Road ~ Chuannanfeng Road)	≥ 0.30	0.15 ~ 0.20
	Jinhai Road (Gongji Road ~ Zhonggang River)	≥ 0.30	0.30 ~ 0.35
	Jindicheng Neighborhood	≥ 0.30	0.30 ~ 0.35
	Dongchenghuayuan I Neighborhood	≥ 0.30	≈ 0.35

4. Simulation results

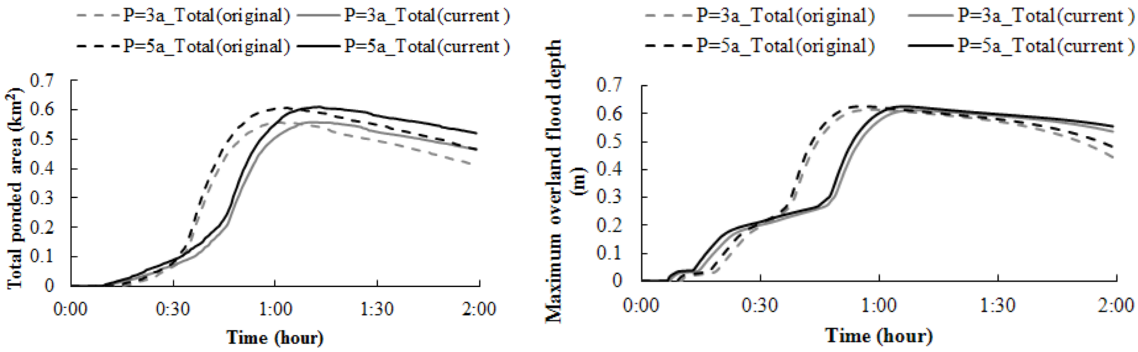
The validated storm flood model is adopted to simulate the overland flood flow in Huinan under the different conditions. And the impact of revising the storm intensity formula on the local storm flood disaster prediction is studied.

In the past, the maximum of the total ponded areas under the various short-duration rainstorms would be 0.556 km^2 at the time of 1:00:36 (P = 3 a, original), 0.606 km^2 at 1:03:36 (P = 5 a, original), and the overland flood depth would be 0.614 m at 1:00:36 (P = 3 a, original), 0.619 m at 1:03:36 (P = 5 a, original) (see Table 4).

Correspondingly, after the formula revised, the maximum areas will increase to be 0.557 km^2 at 1:12:00 (P = 3 a, current), 0.609 km^2 at 1:13:12 (P = 5 a, current), and the flood depth will rise to be 0.615 m at 1:13:12 (P = 3 a, current), and 0.620 m at 1:12:00 (P = 5 a, current) (see Table 4).

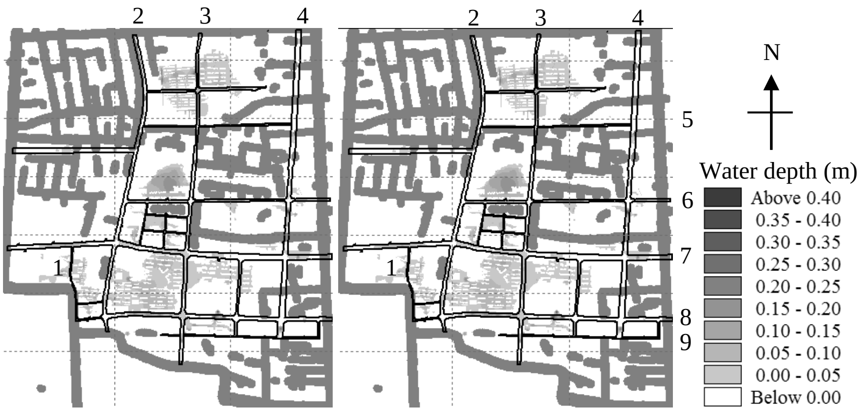
So it can be found that after the storm intensity formula revised, the time of the peak value would be delayed, while the overland flood distribution and its depth have a slight increase (see Fig.6 and Fig.7). And the water level in the manholes would also be a little higher, e.g., the water level in the manhole at the intersection between Jinghai Road and Gongji Road. Before the formula revised, the peak water level reached to 3.75 m (P = 3 a, original), 3.95 m (P = 5 a, original), while the water level would rise to 3.77 m (P = 3 a, current), 3.97 m (P = 5 a, current) (see Fig.8).

Therefore, the drainage system needs to be redesigned with the revised storm intensity formula for the sake of the regional safety.

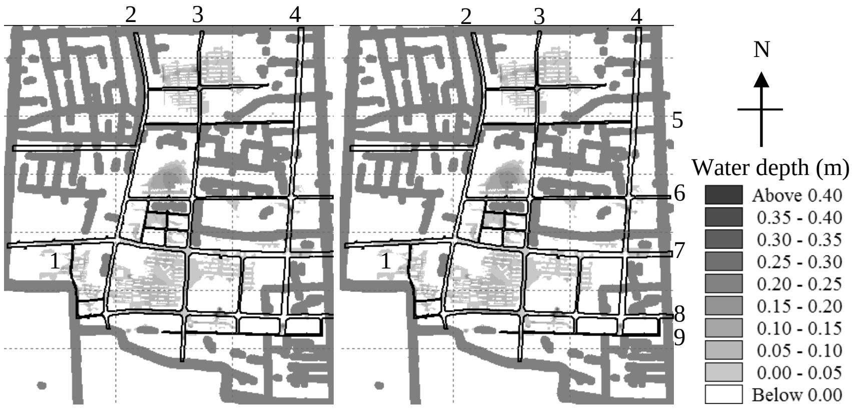


(a) Total ponded area (b) Maximum overland flood depth

Fig.6 Temporal evolution of the total ponded area and maximum overland flood depth under the different conditions



(a) P = 3a_original (at the time of 1:00:36) (b) P = 3a_current (at the time of 1:12:00)



(c) P = 5a_original (at the time of 1:03:36) (d) P = 5a_current (at the time of 1:13:12)

Fig.7 Comparisons of the simulated overland flood distribution under the different conditions (Numbers “1” ~ “9” show Meihua Road, Nanzhu Road, Jinhai Road, Chuannanfeng Road, Tanghong Road, Gongbei Road, Gongji Road, East Renmin Road and Huayuan Road)

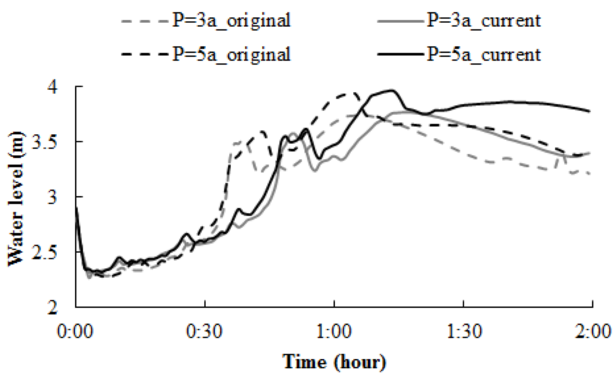


Fig.8 Temporal evolution of the water level in the manhole at the intersection between Jinghai Road and Gongji Road under the different conditions

Table 4 Statistics of the peak ponded area and relevant overland flood depth under the different conditions

	P = 3 a			P = 5 a		
	Original (at the time of 1:00:36)	Current (at the time of 1:12:00)	Changes	Original (at the time of 1:03:36)	Current (at the time of 1:13:12)	Changes
Total ponded area (m^2)	556.496	557.008	0.09 %	606.128	609.664	0.58 %
Overland flood depth (m)	0.614	0.615	0.16 %	0.619	0.620	0.16 %

5. Conclusions

In this research, a numerical model by MIKE FLOOD platform has been set up with coupled the rainfall runoff sub-model and underground network sub-model by MIKE URBAN software, and the overland flow sub-model by MIKE 21 software to simulate the storm flood in Huinan, Pudong District. After the calibration and validation with the actual storm flood disaster happened in Huinan on Oct. 8th in 2013 and Aug. 23th in 2015, the model is adopted to simulate the local overland flood flow under the various short-duration rainstorms before and after the storm intensity formula revised. And the impact of the storm intensity formula on the storm flood disaster prediction is studied. The results are shown that the time of the peak value would be delayed, the total ponded area and overland flood depth have a slight increase, and meanwhile the water level in the manholes would also be a little higher after the storm intensity formula revised. So the drainage pipe networks need to be redesigned under the revised storm intensity formula for safety reasons.

6. References

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