Engineering and Technology Journal e-ISSN: 2456-3358

Volume 08 Issue 04 April-2023, Page No.-2116-2123

DOI: 10.47191/etj/v8i4.04, I.F. – 7.136

Application of Morphologic Analysis to Quantify Diversion of Flood Waterflow and Potential Electrical Energy

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ABSTRACT: As significant catchment of flood water, this study examined important morphological structures of Lake Buhi (LB) catchment area which is a part of Bicol River Basin Area (BRBA). The information taken was used to derive a mathematical model which was then used in analysing the hydrologic event in the area. Different scenarios were investigated to provide solutions and avoid major risks and damages in BRBA during extreme precipitation. The method used to gather the data are Geographical Information System (GIS), digital elevation modelling (DEM), hydrologic modelling, site visit, and remote sensing. It was found that the morphology is well structured to collect and impound vast amount of rainwater flow and form huge body of water known as the LB. The area has immense number of streams that directs surface runoff into the impounded body of water having low drainage density. Enormous amount is needed to discharge away and prevent high water level rise and stop flood in the nearby villages. The capacity of the outflow river is sufficient in most cases of the forecasted precipitation while during the time of typhoon event was found insufficient. However, there are three options to divert away the accumulated floodwater and become a potential source of electrical energy.

KEYWORDS: Morphologic analysis, Lake Buhi, catchment area, Bicol River Basin, hydrologic model

I. INTRODUCTION

The increasing availability of remotely sensed data as inputs for models is driving new directions in hydrological modelling, with a move away from conventional, ground-based measures to systems which assimilate satellite-generated time series of hydrological parameters such as precipitation, evapotranspiration, snow cover, and soil moisture and land cover at different spatial and temporal scales [1]. A river basin is an integrated system where interactions among surface water, and groundwater and their effects on ecosystems take place so that decision-makers require adequate information on these interactions in order to formulate sustainable water resources development strategies [2]. Significances of river basins include provision of drinking water, food, habitat, fossil information, transportation, recreation, hydro-electric power, erosion control, flood control, oceanic recharge and pollution control but among the threats include waste input, excessive water resources exploitation and invasive weeds [3]. Being hazardous to human life and wealth, countries economy, floods are studied by many more authors worldwide with flood frequency analysis of different river basins were carried out using different statistical distributions [4]. In 1975 it was embarked on a plan to develop the BRBA by providing integrated projects for rural development in which environmental studies were done, but the Philippine environmental impact statement requirements were not taken seriously that the resulting environmental assessment was inadequate and failed to predict negative impacts that followed project implementation, particularly in construction of the lake regulation project [5]. The 3000 km^2 BRBA in Southern Luzon Island has extensive low-lying floodplains that the basin lies on the track of many of the typhoons crossing the Philippines and consequently, flood mitigation is a determining factor in multisector development causing the key to poverty alleviation for the many inhabitants who suffer frequent and deep inundation [6].

As part of the BRBA, LB has its own catchment to collect and impound surface water. It is very vulnerable to climate change and weather extremes that the water availability in this lake is highly sensitive to the patterns of changing precipitation [7]. In the extent of extreme precipitation, the storm water being discharged out of this lake causes destructions and extreme flooding that affect large population in the BRBA. Although there are various programs to solve these problems, very few attempts to deal with the uplands and the lake as a single interacting entity and unit to research and development [8].

II. OBJECTIVES

A. General Objective

The main purpose of this study is to make morphological analysis of portion of BRBA which is the LB catchment area.

B. Specific Objectives

Specifically, the objectives of this study are the following: to describe the morphological structure of the area; to derive a hydrologic model that could be used in understanding the extreme waterflow based from the morphological structure; to evaluate the hydrologic performance characterizing a typhoon event using the derived hydrologic model; to explore morphological scenarios that the extreme floodwater be diverted away from the BRBA; and to quantify the potential electrical energy that can be generated based from the explored scenario.

III. METHODOLOGY

The analysis of morphometric aspects supported this study of hydrological models by means of remote sensing and GIS techniques [9]. Morphometric analysis was used as the method for isolation of problem through which precise descriptions of the geometry of landforms was harnessed as data were collected, organized, and analyzed and visualized using remote sensing integrated with GIS techniques to resolve the applications [10]. The data was also obtained through site visit, field survey and by visiting suitable website to acquire the needed satellite feed data. The Geometric Information System (GIS) and Digital Elevation Model (DEM) was used to work with the obtained data. Using satellite remote sensing observations, the estimates of discharge, flow depth, and flow velocity are derived from remotely observed water surface area, water surface slope, and water surface height [11]. Topographic and field surveying technique was found helpful on analysing the relationship between distance, slope, and elevation.

This study was focused on portion of the BRBA which is the LB catchment area. Although, Bicol River basin is defined strictly as the area drained by the Bicol River and its tributaries [12] the lake in which the river originates is continuously supplied with surface water from the LB catchment area making it necessary for a separate analysis. The location is shown in Figure 1. Several equations were applied to analyze the obtained data. To determine if the channel cross section is adequate in accommodating the excessive floodwater, the Manning’s equation was used. The equation is shown below.

$$Q_c = \frac{A}{n}\left(R^{\frac{2}{3}}\right)\left(S^{\frac{1}{2}}\right)$$

Where:

Q_c = discharge capacity of the outflow river channel (m^3/s). To assure that the outflow channel is adequate to hold the discharge of overflowing water, the following condition must be satisfied, $Q_c > Q_o$

A = the cross-sectional area (m^2) occupied by the overflow water. On this study A = 17.71m^2 which was based on the traces of flood flow on sides of the outflow channel.

P = the wetted perimeter (m). This was found by looking on traces of flood flows. P = 27.78m

R = the hydraulic radius is the ratio of the cross-sectional area and the wetted perimeter. R = A/P = 0.64m

S = is the slope of the riverbed

n = is the roughness coefficient in which the river was seen as stable channel with floodplain and firm soil [13].

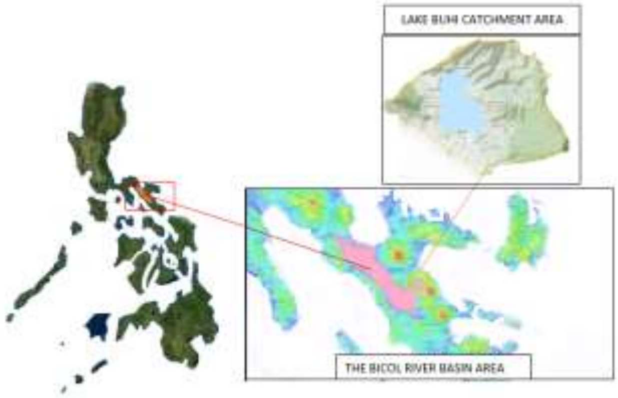

Figure 1. The LB catchment area and the BRBA

The channel outflow capacity was determined using Manning’s equation and the following parameters: narrowest river bed = 24.44m, maximum increase in river depth = 0.67m, cross sectional area = 17.71m^2, hydraulic radius (R) = 27.78, portion of river slope (S) = 1/250, S= 1/340, S=1/540, n = 0.025.

For discharge overflow considering the sluice gate that controlled the water level in the dam is open, the following equation was applied:

$$Q_o = Q_a - Q_s$$

Where:

Q_o = the discharge needed to drain the accumulated rainwater to prevent flooding (m^3/s)

Q_a = Discharge of accumulated rainwater (m^3/s)

Q_s = The outflow discharge in the sluice gate. On this study Q_s = 36.507 m^3/s, a recorded discharge by the sluice gate of the dam with overflowing water [14].

$Q_s = 3.15 \times 10^6\ m^3/day$

The reduction in depth of the water surface of the lake brought by the open sluice gate as outflow discharge was taken by the equation:

$$d = \frac{V}{A_L}$$

$$d = \frac{3,154,204.8m^3}{18,200,000.0m^2}$$

$$d = 0.173m$$

Where:

d = the reduction in depth of the water surface of the lake brought by the sluice gate outflow

A_L = the catchment area of the lake = 18,200,000.00m^2

V = the volume of rainwater disposed from the dam within twenty-four hours through the sluice gate

$V = 3{,}154{,}204.8m^3$

To determine the potential energy of the accumulated water based from the outflow portion of the different option of diverting flood water thru tunnels, the equation is:

$$PE = mgh = pVgh$$

Where:

PE = the potential energy (J)

m = mass of water (kg)

V = volume of the accumulated rainwater (m^3)

g = gravitational acceleration (m/s^2)

p = density of water (kg/m^3)

h = the difference in elevation from the water inflow and outflow of the tunnel. The following equivalent of units were used to convert the unit of Joules (J) to kilowatt hour (kWh):

$$1kWh = 3{,}600{,}000J$$

IV. RESULT AND DISCUSSION

A. Morphological structure of the Catchment area

LB with an area of 18.20 km^2 is part and located at the south eastern portion of the BRBA. The lake is at higher elevation in which the surface water is at more or less 83.00 m elevation in normal weather condition. The surface water of the lake is drained by an outflow through Barit River which is controlled by a dam at coordinate 13.402416, 123.484357. A mini-hydro-electric plant is located on this area. It is supplied by tributary rivers coming from the slope of three mountains namely, Mt. Asog, Mt. Malinao and Mt. Gogo. It is the side slopes of these three mountains that formed into a catchment area confining the collected rainwater into a lake. The combined slope of Mt. Gogo and Mt. Malinao served as wall to prevent the flow of the water directly into the ocean. Without these barrier slope can outflow the water at a shortest distance of 9.00km from the lake to the ocean. The actual situation makes the outflow water to pass through the lowest area making the river contributory to floods in BRBA during extreme rain fall. This made the distance of the river to travel 55.00km in winding direction before reaching the ocean. At normal condition it contributes to irrigate the basin area. The outflow is a tributary river of Lake Baao.

The catchment area is 131.13km^2 which is 7.20 times bigger than the lake. Around the catchment area are combination of the mountain ridges with rugged slopes, rivers and falls. It is on this area that the precipitation water is collected to flow into the lake. Greater precipitation contributes greater amount of surface water in the lake. The highest elevation of the catchment area is 1,150.00m from Mt. Asog, 1,144.00m from the peak of Mt. Malinao and 856.00m from Mt. Gogo. The drainage density of the catchment area at 1.15m/m^2 is at low value. Low values for drainage density can indicate different characteristics, such as higher infiltration rates, lower surface flow velocities and/or lower values of sediment yield transported through river networks while a high drainage density is often related to a high sediment yield transported through the river network, high flood peaks, steep hills, and a low suitability for agriculture [15]. High drainage density is the resultant of weak or impermeable subsurface material, sparse vegetation and mountainous relief [16]. Drainage density which is the ratio of the total length of all the streams and rivers in a drainage basin and the total area of the drainage basin [17] is a degree of how well or how poorly a watershed is drained by stream canals.

Figure 2. The LB catchment area

Stream number reaches 52 number of branches. Stream frequency or drainage frequency is 0.40. This is measured by getting ratio of the total number of stream segments per unit area. Mean stream length which describes the distinguishing assets of drainage grid basin surfaces is 2.81km. Relative relief or total relief which is the elevation difference between the lowest and the highest point is 1.075 [18].

Table 1. The morphologic parameters of the catchment area

Parameters	Quantity
Stream Number	52
Drainage density	1.15
Stream frequency	0.40
Mean stream length	2.81km
Relative relief (Total Relief)	1.075

Catchments with steeper slopes, less erodible soil texture, larger impermeable areas, shallower soil depth, and smaller catchment areas are prone to sharper flood peaks [19].

B. The hydrologic model based from morphologic structure of the area

This study used the runoff model which is defined as a set of equations that helps in the estimation of runoff as a function of various parameters and is used for describing watershed characteristics using two important inputs such as the rainfall data and drainage area [20]. Using the catchment area from the morphological study, the total volume (V) of accumulated precipitation at certain period of time is:

$$V = 131.13km^2\left(1000\frac{m}{1km}\right)^2 P(mm)\left(\frac{1m}{1000mm}\right)$$

The unit of V in the equation is $m^3$and P is in mm. By simplifying the equation and derivation of units become:

$$V = 131{,}130P$$

To find the increase in depth (H) of the lake at certain period of accumulation, the equation was divided by the area of the lake (A_L) and the equation becomes:

$$H = \frac{131{,}130P}{A_L}$$

The unit of the increase in depth of the lake water is meter (m). To effectively study the lakes, it's important to quantify the total lake volume which is hasn't been possible as the existing satellite methods cannot estimate the bathymetry depth, but it has been presented a framework to monitor the volumetric fluctuation of the inland water body by the combination of a bathymetry map, an optical satellite imagery & multiple satellite altimetry measurement [21]. To compute the amount of river discharge outflow (Q_o) from the that the accumulated rain water might not gain increase in depth at the time of accumulation, the derived equation for 24 hours is:

$$Q_o = \frac{131130P}{(24Hr)\left(\frac{60\text{min}}{Hr}\right)\left(\frac{60\text{sec}}{\text{min}}\right)}$$

In which by simplifying becomes:

$$Q_o = 1.52P$$

To settle that the outflow river is sufficient to accommodate the flood water must satisfy the following equation:

$$Q_c > Q_o$$

Where:

Q_c = discharge capacity of the outflow channel

C. Hydrologic performance analysis

The satellite rainfall forecast [22] for typhoon Ulyses (VAMCO) using Global forecast system (GFS) model was applied to analyze the hydrologic performance in the area. The forecasted rain fall data for four days and the computed volume of the accumulated rainwater is shown in Table 2. Surface runoff in the analyses is in full subsequently that the previous days of accumulation was already showered with heavy precipitation. On this case, it was assumed that for long duration of rainfall, saturation and infiltration is excessive to be influenced by soil properties, land cover, hill slope and vegetation [23], [24] hence the effect of losses on surface runoff was neglected in the analysis.

Table 2. The four days forecasted precipitation and the accumulated volume of rainwater

Day	Date	Rainfall* (mm) Source: MGB, 2020	Accumulated volume of rainwater (mm)
1	November 10	9.9	15.80
2	November 11	196.7	212.50
3	November 12	16.60	229.10
4	November 13	3.80	232.90

The rainfall data was used to compute the volume and discharges due to rain water accumulation. Situations were considered that the accumulated rainwater is not released from the outflow river while another case is when the sluice gate is open to release the excessive water. The quantified result is shown in Table 3.

Table 3. Volume, discharge and depth of rainwater accumulation

Dam situation	Parameters					
	Accumulated rainwater			Channel Outflow Capacity by Manning's formula (m^3/s)		
	V	d	Q_o	S_1	S_2	S_3
Day 1						
SGC	1.30	0.07	15.05	A	A	A
SGO	-1.08	-0.10	-21.46	A	A	A
Day 2						
SGC	25.79	1.42	298.98	NA	NA	NA
SGO	22.63	1.25	262.47	NA	NA	NA
Day 3						
SGC	2.18	0.11	25.23	A	A	A
SGO	-0.97	-0.06	-11.28	A	A	A
Day 4						
SGC	0.50	0.03	5.78	A	A	A
SGO	-2.65	-0.14	-30.73	A	A	A

Note:

V= Volume of accumulated rainwater in the lake in $1x10^6$ m^3

d = Increase in depth (m)

Q_o = discharge to drain for 1 day (m^3/s)

S_1 = slope of the channel outflow at 1/250 with discharge capacity
of 33.22 m^3/s by Manning's equation

S_2 = slope of the channel outflow at 1/340 with discharge capacity
of 28.49 m3/s by Manning's equation

S_3 = slope of the channel outflow at 1/540 with discharge capacity
of 22.61 m^3/s

SGC = sluice gate is closed that rainwater is unreleased in the dam

SGO = sluice gate is open that rain water is released from the dam

A = the amount of accumulated rainwater is adequate to be accommodated by the outflow channel

NA = the amount of the accumulated rainwater is not adequate to be accommodated by the outflow river

The table shows that on day one of rainwater accumulation (A) the total volume (V) is $1.30x10^6$ m^3. With sluice gate open, the remaining impounded water is will reduce to below normal of $-1.08x10^6$ m^3. In this case, there is no need to release such amount of water for it will not cause damage and flooding in the nearby villages of the lake. Not releasing such amount of water is needed as reserve for the preceding days with no rainfall event in the area. The structure is safe against the forces such as water pressure, tail water pressure, uplift pressure, silt pressure and earthquake forces that make the dam unstable to cause overturning, sliding, and tension effects on the dam [25]. The amount of discharge of rainwater accumulation in the dam is 15.05 m^3/s which is sufficient to be accommodated by the outflow river considering slopes of s_1 and s_2 to attain normal water level while it is insufficient on portion with slope s_3 however with the sluice gate open will not compensate that such amount of discharged water is not enough to be impounded in the dam. On this situation, the portions of the river even with low amount of slope are not problems to have delay bank return flow by more than four times compared with vertical river banks and saturated flow [26] similarly with width which can be directly associated with the magnitude of the meander wavelength, catchment area, and discharge which is more closely related to the range of possible values of slope and sinuosity [27].

On day 2, the outflow channel at portions with slopes S_1, S_2 and S_3 are insufficient to accommodate the excessive floodwater to discharge an amount of 298.98 m^3/s which is similar even if the sluice gate of the dam is open to discharge outflow water at 262.47m_3/s. This situation causes flood water rise and overflow in the dam which is dangerous to the surroundings particularly if the sluice gate is not opened. The flood discharge sluicing gate is only opened when the overfall dam cannot meet flood discharge requirement while the overflow capacity of discharge through gate opening have to be calculated according to the flow rate of the opening [28].

At days 3, the outflow channel has to discharge more than 25.25m^3/s, which is insufficient for out flow river with slope S_3 to discharge such amount of rainfall water. Both soils and slopes, unit flow discharge and sediment concentration increased with increasing flow rate however the effect of slope gradient on flow discharge depends on soil type [29]. Upstream river slope and roughness are necessary in estimating the upstream drainage area runoff and design of the downstream river structure [30]. It is apparent on the data that as the accumulation of rain water continues, there is continues increase in water depth, however with open sluice gate can accommodate the accumulated rain water.

The accumulated rainwater on day 4 of 5.78 m^3/s is sufficient to be accommodated by the catchment area with effect of the decrease of water level in the lake. When water levels are low, these demands are backed by claims that water loss is driven by human intervention and should be compensated through human intervention, however, when water levels are high the demands for human intervention to increase outflows through water diversions and increased dredging arise, even though persistent increases are attributed to direct human intervention [31].

D. Morphological scenarios of diverting the floodwater

Scenarios can serve as points of reference in the future for decisions that we have to make today as morphological analysis provides a structured method for ensuring consistency and relevance in scenario development [32]. Located at higher elevation, there are possibilities that the outflow water could be diverted not to pass to the typically flooded BRBA. There is even a possibility that the lake be drained completely. That is by putting diversion tunnel of the outflow water. However, draining the lake is not a practical option for the lake will lose the international pride as being the home of the smallest fish in the world with scientific name Mistichthys Luzonensis [33].

Although, properly designed outflow channel from LB can minimize flood in the surrounding villages the outflowed water may affect the lower portion of the BRBA. It is the place where most villages are affected by flood. Flood-prone areas are the place where poor people tend to live, and that floods can cause and exacerbate poverty that tangible measures need to be taken to protect against floods and to help the poor escape from the vicious cycle that they are trapped [34].

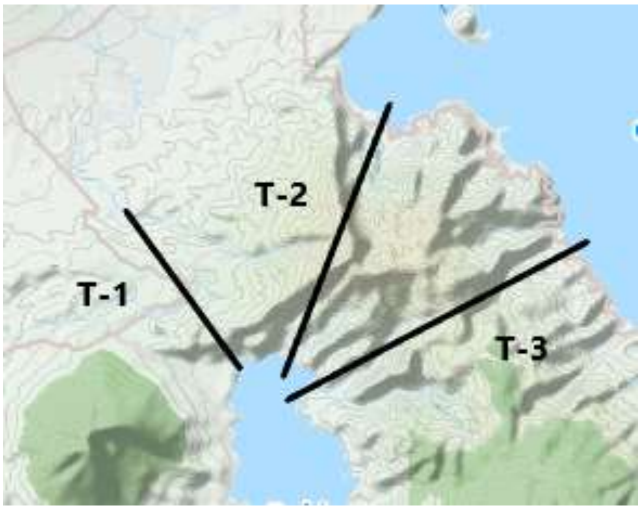

Figure 3. Possible location of the flood water outflow

There are three scenarios (T1, T2 and T3) that the outflow water could be diverted (See figure 3). The scenarios could be done by constructing diversion tunnel. Previous studies had been conducted to examine the system operation of diversion tunnel in terms of their flood season spillway release reducing effects and water supply during water utilization periods and with regard to connected reservoir operations were able to addressed the comprehensive analysis of hydroelectric power generation, water quality improving effects, and economic and sociological benefits [35]. As the seasonal changes nowadays are unpredictable, an underground water diversion system is an excellent remedy to an extent that it has various advantages in areas of thickly populated with buildings and no other remedies could be constructed above the ground [36].

E. Potential Electrical Energy

Diverting of flood flow can produce electrical energy. The quantity of the potential electrical energy that can be generated based from the presented scenario presented in Table 4.

Table 4. Direction of outflow tunnel, distance, elevation and the potential energy from the accumulated rainwater

S	Coordinate		HD (Km)	DE (m)	PE (10^6 kWh)			
	From	To			Day of accumulation			
					1	2	3	4
T1	13.482285, 123.497775	13.532623, 123.459146	6.98	23	0.08	1.61	0.14	0.03
T2	13.484120, 123.514498	13.562741, 123.536524	9.06	81	0.28	5.69	0.48	0.11
T3	13.479029, 123.520006	13.506990, 123.612340	10.61	81	0.28	5.69	0.48	0.11

Note:

S = scenario to divert flood water
HD = horizontal distance in kilometers (Km)
DE = difference in elevation in meters
PE = potential electrical energy in kilowatt-hours (kWh)

Table 4 reveals that with given coordinates, T1 would provide the shortest horizontal distance (HD), difference in elevation (DE) and potential energies (PE) as the outflow tunnel with T1 as the easiest and cheapest situation to be constructed. It also has the least problems in terms of political boundaries since both the inflow and outflow of the tunnel are located in the same congressional district. Thus, it is adoptable that budgeting and management of the construction be handled by in the district. However, implementing such project may give risk to few villages outside BRBA. Flood water if diverted away from larger population area is an advantageous option thinking that new water reservoir could be constructed to supply new areas for agriculture, hydroelectric power source, domestic water supply, recreation and tourism activities outside BRBA. In a study of risk analysis of floodwater resources utilization along water diversion project, it was found that the risk is the highest and the benefit is relatively higher in the wet year, the risk is lower in the flat year and the benefit is similar to that in the wet year, and the risk is the lowest in the dry year, but the benefit is the lowest [37]. The horizontal distance, difference in elevation and the potential energies for T2 and T3 are much greater compared to T1 indicating that the option of constructing of the tunnels are more expensive. Using either of the two options is the safest compared to T1 for the diverted flood flow is away from populated village. However, they are more complicated in terms of political boundaries as inflow and outflow of T2 belongs to different district. The situation could be implemented with the jurisdiction of the provincial government. With the inflow and outflow of T3 belong to two different provinces is in need of the national government intervention to implement the situation. Both T1, T2 and T3 have remarkable potential energies that could be a source of bigger hydroelectric power plant. Energy scenarios have long been successfully used to inform decision-making in energy systems planning, with a wide range of different methodological approaches for developing and evaluating them [38].

CONCLUSIONS

As significant catchment of flood water, this study examined important morphological structures of LB catchment area which is a part of BRBA. The information taken from the morphological study was used to derive a mathematical model which was then used in forecasting and analysing the hydrologic event in the area. Different scenarios were seen to be investigated to divert and avoid major risks and damages in BRBA. It was found that the morphology is well structured to collect and impound vast amount of rainwater flow to form a huge of body of water which is known as the LB. The area has immense number of streams that directs surface runoff into the impounded body of water having low drainage density. The forecasted four days of peak rainfall data was used to find that the area could collect huge volume of rainfall water. Enormous amount is needed to discharge away and prevent high water level rise to stop flood in the nearby villages. The capacity of the outflow river is sufficient in most cases of the forecasted precipitation while on the time of typhoon event was found insufficient to outflow the accumulated floodwater. The accumulated rainfall water is sufficient to contribute flood in BRBA however there are three options that were seen to divert away the accumulated floodwater from BRBA and become a potential source of electrical energy based from the morphological structure of the area.

ACKNOWLEDGEMENT

The researcher would like to acknowledge the support extended by the PSU administration through the leadership of President Dr. Raul G. Bradecina, Vice President for Research and Extension Patricia Candelaria and Research Director Luisa Lanciso specially when it comes to financial and moral obligation.

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