Impacts of Barrage Flushing and Flooding-in Operations on Saline Intrusion Upstream

Law, I.N.[1], Oon, Y.W.[2], Law, P.L.[3], Kho, F.W.L.[4]

Abstract-This research looks into the effects of barrage flushing and flooding-in operations on upstream salinity versus discharge over time. Water samples for salinity levels were collected over a period of 33 hours from two locations upstream of Sarawak Barrage, i.e., at 1.5 km and 6 km. During flooding-in operation, salinity levels increased by approximately 13.8 ppt at 1.5 km upstream, and by 0.2 ppt at 6 km upstream after 3 hours into the operation. At 6 km upstream, negligibly low saline levels ranging from 0.5 to 2.5 ppt were detected, regardless of sea tide levels and flow rates through barrage gates. Rate of saline water propagation towards upstream was estimated to be approximately 5 km/hour during flooding-in operation. During flushing operation, it was noticed that waters flowed smoothly from upstream through the barrage gates to downstream without generating noticeable turbulences, whereby salinity levels at 1.5 km upstream dropped from approximately 11.7 to 4.7 ppt over a period of 3 hours. After 3 hours of gates closure, it was observed that salinity levels upstream of the barrage dropped by approximately 1.4 ppt at Pending (1.5 km upstream), and by 0.5 ppt at Satok (6 km upstream). From this study, it was also found that the differences in the rates of increase and decrease in salinity levels at a particular point upstream of the barrage over a period of 3 hours during flooding-in and flushing operations were negligibly small (<1 ppt).

Keywords: Barrage, flushing, draining-out, flooding-in, saline intrusion, salinity

I. INTRODUCTION

Generally, a "barrage" structure can be defined as a relatively low-level dam with controlling gates constructed across a river to raise the river level sufficiently to divert the flow in full or in part, into a supply canal or conduit for the purposes of tidal control, irrigation, industrial uses, domestic, and so on [1, 2]. Figure 1 illustrates Sg. Sarawak Regulation Scheme (SSRS), whereby Kuching City is located in tidal influence zone with a tidal range of approximately 6 meters [2, 3]. To control upstream water level in Sg. Sarawak, a barrage was constructed in 1988, i.e., Sarawak Barrage to regulate draining-out (flushing) and to prevent seawater from flooding-in (Figure 1) [4]. Thus, two causeways were constructed across Sg. Santubong and Sg. Sarawak, namely Bako Causeway and Sarawak Causeway, respectively. Runoffs or waters from catchment of Sg. Sarawak are diverted to flow through the Sarawak Barrage, the sole outlet (Figures 1 and 2) [1, 5]**.** Figure 3 illustrates the discharge characteristics through barrage gates, and Figure 4 shows the general arrangement of Sarawak Barrage. As shown in Figure 4, the barrage structure consists of 5 radial gates (25 meters in width each) to prevent saline intrusion and to regulate water levels upstream of the barrage [1, 5]. A ship lock was constructed alongside of the barrage, exclusively reserved for river traffic (Figure 4).

The main objectives of constructing the barrage structure across Sg. Sarawak are to control flooding of Kuching City and to prevent or minimize saline intrusion to or beyond Kuching City and Batu Kitang Water Treatment Plant. The barrage also serves as a "mini dam or weir" by holding additional amount of fresh water behind it during low tide to maintain required water level upstream [1, 6]. The barrage would provide sufficient volume of water for Batu Kitang Water Treatment Plant located approximately 15 km upstream of the barrage. Additionally, the construction of barrage would create aesthetic value of Kuching Water Front along Sarawak River located at immediate upstream of Sarawak Barrage. Feasibility study shows that there are more pros than cons by constructing a barrage structure to maintain required water level behind it than to construct a dam upstream of Kuching City [1, 6]. Furthermore, catchment of Sg. Sarawak is the drinking water supply source for more than half a million of residents in Kuching City [1, 7].

[1] Law, I.N., MSc Student (SLUSE Program), FSTS, Universiti Malaysia Sarawak (e-mail: puonglaw@feng.unimas.my)
[2] Oon, Y.W., PhD Student of Civil Engineering Department, Universiti Malaysia Sarawak (e-mail: yinwee3@yahoo.com)
[3] Law, P.L., Professor of Civil Engineering Department, Universiti Malaysia Sarawak (e-mail: puonglaw@feng.unimas.my)
[4] Kho, F.W.L., PhD Student of Faculty of Engineering, Universiti Malaysia Sarawak (e-mail:frexwl@gmail.com)

Sg. Sarawak Barrage Management (SSBM) commenced the operation of Sarawak Barrage in August 1998 by carrying out daily flushing operation during low tide and alternate weekdays flooding-in operation during high tide [4]. One of the major considerations during flushing or flooding-in operation is to maintain the required water level upstream of Sarawak Barrage. During draining-out or flushing operation, all the five gates (Figure 3 and 4) would be lifted up from river bottom by 1.0 meter [5]. The frequency of flushing operation during rainy season may be increased depending on information on catchment rainfall intensity and duration provided by telemetry stations installed upstream and within the catchment of Sg. Sarawak [4]. Flooding-in operation is carried out on every Monday, Wednesday and Friday to specially provide the required water levels for shipyard maintenance activities located at the immediate upstream of the barrage. Flooding-in operation would be stopped when river water level equates with seawater level [4]. Generally, the duration of flooding-in operation is less than 1 hour to prevent excessive saline intrusion that may reach the major water treatment plant at Batu Kitang located at about 15 km upstream of Sarawak Barrage. Prior to the construction of the barrage, saline intrusion could reach Batu Kitang Water Treatment Works and saline contamination in the treated water had been a major problem during dry season [8].

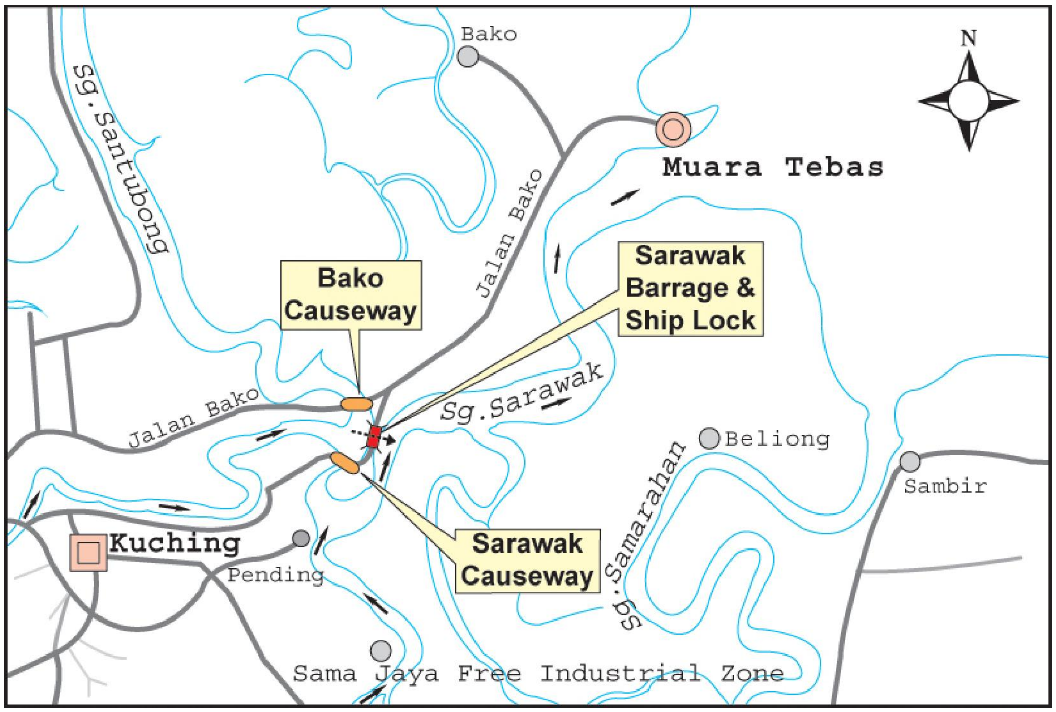

Figure 1: Sg. Sarawak Regulation Scheme [4]

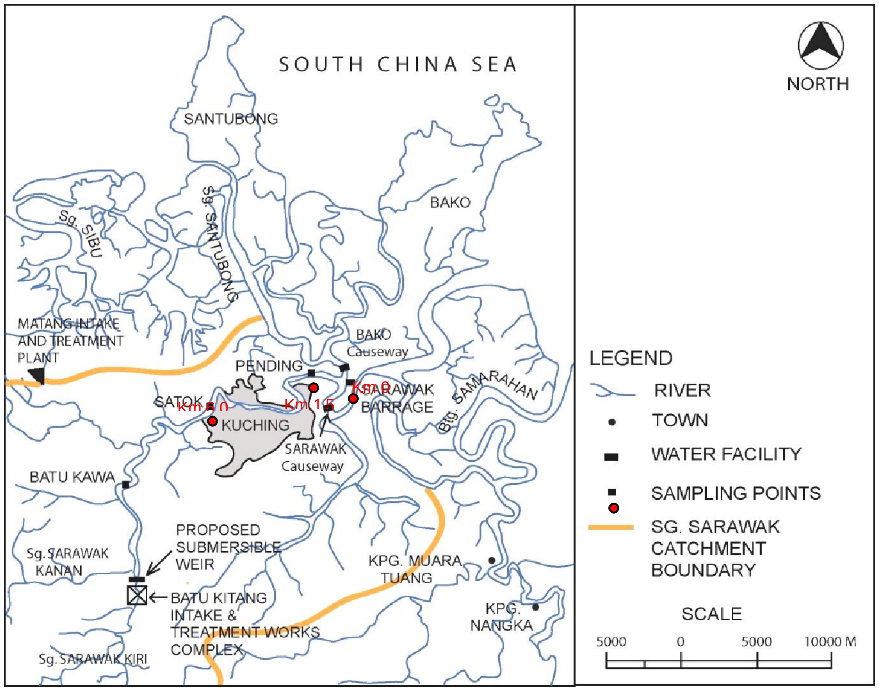

Figure 2: Salinity Monitoring Locations at Pending and Satok [4]

In general, the operation of Sarawak Barrage can have significant impact on the water quality upstream in spite of the high annual rainfall experienced in the catchment [1, 9]. Undoubtedly, the effect of barrage operation on water quality is most significant during dry season [1, 10]. Based on the information provided by Sg. Sarawak Barrage Management (SSBM), the main reason to regulate water levels in Sg. Sarawak is aimed to provide an acceptable water intake level at Batu Kitang Water Treatment Plant, approximately 15 km upstream of the barrage [11]. Figure 1 shows the layout of Sg. Sarawak Regulation Schemes (SSRS) outlining the locations of Sarawak Barrage, Bako Causeway, and Sarawak Causeway [1, 5]. In this study, water monitoring points included Pending point at 1.5 km, and Satok point at 6 km upstream of Sarawak Barrage (Figure 2).

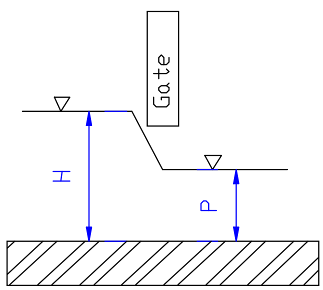

Figure 3: Discharge through Barrage Gates during Flushing and Flooding-in Operations [1]

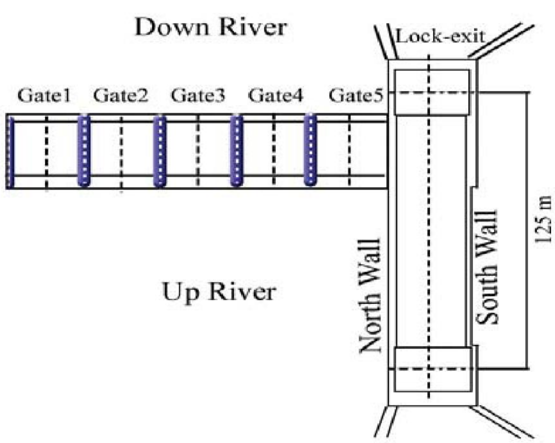

Figure 4: Layout of Sarawak Barrage with a Ship Lock [1]

II. MATERIALS AND METHOD

Hypothetically, draining-out (flushing) and flooding-in operations can create upstream turbulences and salinity intrusion in the river stretching from the barrage and propagates upstream [1]. In this study, water samples were collected at 3-hour interval over a period of 33 hours, i.e., from 17th to 19th August 2000 during flushing and flooding-in operations (Table 1). Water samples for salinity levels were collected from two monitoring locations upstream of the Sarawak Barrage, namely at Pending and Satok points from the surface (1.0 meter below water surface), mid-depth and bottom (1.0 meter from the bottom of riverbed).

Table 1: Tide Levels and Barrage Gates Scenarios [1]

Hour	**Tide Level**	**Barrage Gates**
0 - 3	High	Closed
3 – 9	Low	Open
9 – 15	High	Open
15 – 21	Low	Closing at 15th hour Fully closed at 18th hour
21 – 27	High	Closed
27 – 30	Low	Open
30 – 33	Low	Open

Barrage gates are opened during low-tide for flushing to take place, and are closed during high-tide to prevent saline intrusion. In this study, salinity levels at the individual levels were determined at 3-hour intervals during flushing and flooding-in operations. Synchronized timing sequence for the opening and closure of barrage gates with respect to tide levels, timing of flushing and flooding-in is shown Table 1. During sampling period, barrage gates were opened during low-tide (flushing) from 3rd to 9th hour; and during high-tide (flooding-in) from 9th to 15th hour. Barrage gates were closed from 18th to 27th hour, and remained open from hours 27 to 33. During normal barrage operation, gates are closed during high-tide (flooding-in) and opened for flushing operation during low-tide.

Flow velocity measurements (m/s) were recorded at the barrage during flushing and flooding-in operations, and the volumetric discharge values (m^3/s) were correlated with changes in salinity levels upstream. Auxiliary outputs from these measurements were volumetric discharge versus water levels at the individual monitoring points. Volumetric discharges were then correlated with salinity levels. In this study, volumetric discharges during flushing and flooding-in operations through the horizontally-crested weir were determined using the following equations [12]:

$$Q = CLH^{\frac{3}{2}} \quad (1)$$

$$C = 1.78 + 0.24\frac{H}{P} \quad (2)$$

Where Q = Discharge, m^3/s
C = Discharge Coefficient
L = Width of Gate, m
H = Higher water level, m
P = Sill height, m

Volumetric discharge changes with respect to water levels at the individual water sampling stations. When higher water level (H) is reduced to the same level as sill height (P), either flooding-in or flushing operation would cease [1, 12]. Total length of the gate (L) is dependent on the number of gates opened from bottom by 1.0 meter during flushing or flooding-in operation. This study attempted to correlate discharge with salinity during flushing and flooding-in operations by determining upstream salinity levels. Saline intrusion intensities were analysed and correlated with flooding-in and draining-out operations. Secondary data from Lembaga Air Kuching (LAK) were also used to compare with changes in salinity levels upstream during flooding-in and flushing operations.

III. RESULTS AND DISCUSSION

Plots of salinity levels versus discharge over time through the barrage for Pending and Satok monitoring points are illustrated in Figure 5. In Figure 5, positive discharge values indicate flushing operation, negative discharge values indicate flooding-in operation, and zero discharge indicates that all the five barrage gates were closed during sampling time, whereby neither flushing nor flooding-in activity occurred. Details of volume of discharge through barrage over time, barrage gates operational modes, and salinity (in parts per thousand, ppt) levels upstream during sampling period are shown in Table 2. It was shown that Sarawak Barrage flushing and flooding-in operations had significant impact on saline intrusion upstream of barrage structure.

Table 2: Salinity versus Discharge over Time

Time, Hour	**Operation Mode**	**Discharge Through Barrage Gates, m^3/s**	**Salinity at Pending, ppt** (1.5 km upstream)	**Salinity at Satok, ppt** (6 km upstream)
0	Neutral	0.00	1.0	0.0
3	Neutral	0.00	0.5	0.0
6	Flushing	6,674	0.0	0.0
9	Flushing	4,132	0.0	0.0
12	Flooding-in	-3,768	8.0	0.0
15	Flushing	2,903	13.8	0.0
18	Neutral	0.00	14.5	0.5
21	Neutral	0.00	13.1	0.0
24	Neutral	0.00	11.2	0.0
27	Neutral	0.00	9.6	0.0
30	Flushing	2,499	11.7	0.0
33	Flushing	4,475	4.7	0.0

Plots of salinity levels in parts per thousand (ppt) against discharge (m^3/s) over time (hours) over a period of 33 hours, i.e. from 0^{th} to 33^{rd} hour are illustrated in Figure 5. During water sampling period, it was noted that 0^{th} to 3^{rd} hour experienced a regime of high tide whereby barrage gates were closed to prevent or minimize saline intrusion. Salinity levels at Pending (1.5 km upstream) ranged from 0.5 to 1.0 ppt, while Satok (6 km upstream) recorded zero ppt during this regime.

Hours 3 to 9 experienced a regime of low tide whereby barrage gates were opened for flushing operation to take place. Discharge volume through barrage gates accelerated from Q=0 m^3/s at hour 3 to Q=6,674 m^3/s (peak flow) at hour 6. At hour 6, peak discharge occurred and salinity levels recorded zero ppt at both Pending and Satok. Salinity levels were not detected at 1.5 km upstream after 3 hours of flushing. During flushing operation, water flows smoothly from upstream through the barrage gates to downstream without generating noticeable turbulence. However, upstream noticeable turbulences were observed immediately after closure of barrage gates. During flushing operation, waters flow from upstream to downstream imparting a trust against the barrage gates creating surges or waves in the upper stretch of the barrage. The waves travels upstream, and the surge energy increases when flushing operations is immediately followed by flooding-in operation without closing the gates. However, total suspended solids levels at the individual points are not solely due to turbulences created during flushing or flooding-in operation, but also constitute materials from upstream riverbanks, riverbed and drainage effluences.

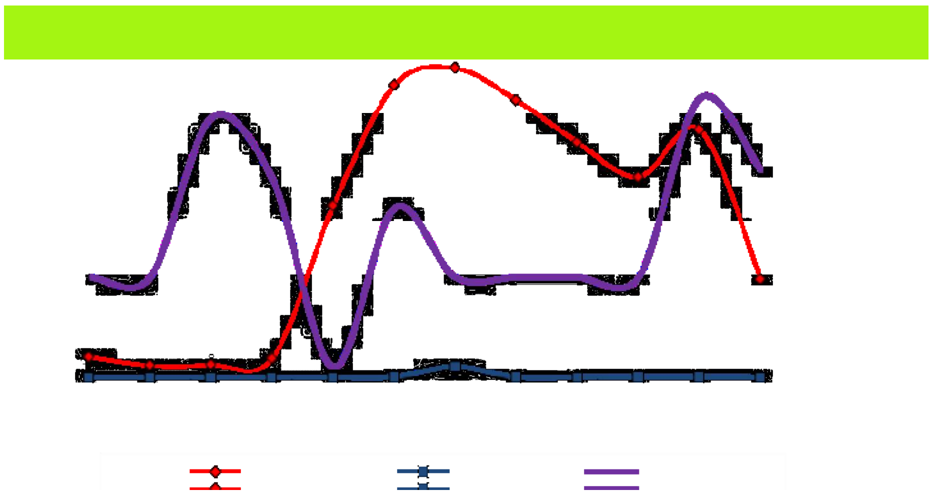

Figure 5: Salinity versus Discharge over Time at Pending (1.5 Km) and Satok (6 Km) Monitoring Points

During sampling period, hours 9 to 15 experienced a regime of high tide and barrage gates remained open for flooding-in operation to take place. Noticeable flooding-in through barrage gates started approximately at 11th hour. As shown in Table 2, salinity levels increased from zero to 13.8 ppt at Pending, and from zero to 0.2 ppt at Satok. During flooding-in operation, there was a dramatic increase in salinity levels at Pending, and negligible increase in salinity at Satok. Hour 15 marked the end of high-tide regime, whereby flooding-in operation stopped and flushing began. During hours 9 to 15 regime, it was noted that Pending point (located 1.5 upstream of barrage) recorded maximum salinity level of approximately 13.8 ppt at hour 15.

During sampling period, flushing operation occurred during low-tide regime between hours 15 and 21. However, in this study an attempt was made to determine the intensities of saline intrusion upstream by stopping flushing operation during midway of low-tide. Thus, at hour 18, barrage gates were fully closed. Upstream salinity levels at Pending recorded 14.5 ppt and Satok recorded 0.5 ppt at hour 18, i.e., immediately after closure of barrage gates (Table 2). Three hours after barrage gates were closed, i.e. at hour 21, salinity dropped from 14.5 to 13.1 ppt at Pending, and dropped from 0.5 ppt to zero ppt at Satok (Table 2). In this study, it was demonstrated that the effects of gate closure after 3 hours into flushing operation on upstream salinity levels were indirectly proportional to upstream distance from barrage.

Hours 21 to 27 fell into a regime of high tide and the barrage gates remained closed to prevent saline intrusion. Generally, flushing operation lasts for 6 hours, which covers the entire regime of low tide. However, one of the primary objectives of this study focused on upstream salinity levels by stopping flushing operation during midway of low-tide, i.e. barrage gates were closed at hour 18. Thus, barrage gates were closed (at hour 18) during the last 3 hours of low tide, which was supposedly having flushing operation. From hours 18 to 27, salinity levels for the two monitoring stations decreased from peak level recorded 14.5 ppt at hour 18 (when the gates were initially closed) to 9.6 ppt at hour 27, and then increased to 11.7 ppt at hour 30 before the gates were opened for flushing operation (Table 2). At hour 30, gates were opened for flushing and after 3 hours of flushing, salinity levels at Pending dropped from 11.7 ppt to 4.7 ppt. The salinity levels were comparatively higher than flushing operation from hours 3 to 6. Thus, a comparatively higher salinity levels were recorded at hour 33 than hour 6 after 3 hours into flushing operation. This could be attributed to the fact that when barrage gates were closed at hours 18, saline residuals during previous flooding-in operation remained in the upstream at hour 27 would superimpose on current level of saline contained in the current flooding-in seawaters.

At Pending, salinity levels increased from 0 ppt at hour 9 to 8.0 ppt at hour 12, which accounted for 8 ppt of increase over 3 hours of flooding-in operation. Salinity levels dropped from 11.7 ppt at hour 30 to 4.7 at hour 33, which accounted for 7 ppt drop over a period of 3 hours flushing operation. The results show that the difference in rate of increase and decrease in salinity level at a particular point upstream over a period of 3 hours during flooding-in and flushing operations are negligibly small. For instance, at Pending (1.5 km upstream of barrage), the difference is 1 ppt. Thus, it can be concluded that negligible amount of longer time may be required to drain out saline content as compared to flooding-in to attain same level of salinity at a particular point upstream. Satok monitoring point is located approximately 6 km upstream of barrage whereby negligibly low saline levels (peak ≤2.5 ppt) were detected regardless of tide levels and flow rates through barrage gates. To partially overcome saline intrusion beyond barrage, de-silting operation may be introduced and implemented. Desilting operation requires that barrage gates be opened partially to about 1.0 m high. The gates would function like orifices and upstream waters would be drained out through the bottom of the barrage gates. As saline water has a relatively higher density than fresh water, de-silting operation would drain saline water out through the bottom of the barrage gates.

IV. CONCLUSIONS

During flooding-in operation, noticeable flooding-in could be seen and salinity levels increased by 13.8 ppt at Pending (1.5 km upsteam), and by 0.2 ppt at Satok (6 km upstream) over a period of 3 hours. During this regime, maximum salinity level recorded at Pending was 13.8 ppt after 3 hours into flooding-in operation. However, saline intrusion did not extend beyond 6 km upstream regardless of sea tide level and flow rate through barrage gates. Rate of propagation of saline water upstream was estimated to be approximately 5 km/hour during flooding-in operation.

During flushing operation discharge volume attained the peak 6,674 m^3/s after 3 hours into the operation. During this regime, waters flowed smoothly from upstream through the barrage gates to downstream without generating noticeable turbulences, and salinity levels dropped from 11.7 to 4.7 ppt over a period of 3 hours. The effects of stopping flushing operation during mid-time (i.e. 3 hours after closure) on saline intrusion show that upstream salinity levels dropped by 1.4 ppt at Pending (1.5 km upstream), and by 0.5 ppt at Satok (6 km upstream).

The differences in rates of increase and decrease in salinity levels at a particular point upstream over a period of 3 hours during flooding-in and flushing operations were negligibly small. For instance, at Pending (1.5 km upstream of barrage), the difference between rates of increase and decrease in salinity levels is 1 ppt. Satok monitoring point is located approximately 6 km upstream of barrage whereby negligibly low saline levels ranging from 0.5 to 2.5 ppt were detected regardless of sea tide levels and flow rates through barrage gates.

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