

Flow Characteristics and Bed Morphology in a Compound Channel between Two Single Channels

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Abstract: In mountainous areas, a river can widen from a single channel to a compound channel under the influence of geological conditions or human impacts, bringing about challenges in terms of flood control and channel regulation. This paper reports the results of tests conducted in a 26 m long flume with a uniform sediment bed (grain size = 0.5 mm), investigating the flow characteristics and bed morphology in a compound channel between two single channels. The stage-discharge relationship in the compound channel and the longitudinal and cross-sectional bed profile in the compound channel between two single channels are presented and analyzed. The experimental results indicate that the flow characteristics and bed morphology in a compound channel between two single channels are significantly different from those in a normal compound channel. Based on the experimental data and observations, the mechanisms of flow and sediment transport in the compound channel between two single channels are illuminated.

Keywords: compound channel; flow characteristics; bed morphology; sediment transport

1. Introduction

A river can widen from a single channel to a compound channel with floodplains due to the influence of geological conditions or human factors (e.g., the Tongluoxia reach, the Qutangxia reach of the Yangtze River, the Pengshan reach of Min River (Figure 1), etc.). Floodplains are important sites of production and human habitation and are commonly used as arable land. For river flood control and channel regulation, it is important to study the flow characteristics and bed morphology in a compound channel between two single channels.

Many studies have investigated the flow characteristics and sediment transport in compound channels (i.e., rivers have a main channel with floodplains) [1–8]. In a compound channel, as the bankfull flow reaches the floodplain, the sudden increase in the wetted perimeter reduces the hydraulic radius significantly. Thus, conclusions based on single channels may not be applicable to compound channels [9–14]. The conventional divided cross section method divides a compound channel into a main channel and a floodplain by making a plumb line along the boundary. However, this method does not consider the shear stress between the main channel and the floodplain, causing a large calculation error [15,16]. Wright [17] found that the vertical division method overestimated the flow discharge when the relative water depth (the ratio of the floodplain flow depth to the main channel flow depth) was below 0.5. Based on a force balance between the floodplain and the main channel, Liu and Dong [18] derived a predictor for calculating the flow discharge in compound channels under steady flow conditions. Ackers [19–21] modified the divided cross section method based on the concept of river channel coherence (COH), introducing the discharge correction factor (DISADF) and the discharge error factor (DISDEF) to correct the calculated flow Q_{basic} in compound channels.

Based on the Navier-Stokes equation, Shiono and Knight [22] proposed an analytical solution for the vertical average velocity in compound channels. In a compound channel, the sediment moving from the floodplain to the main channel is coarser than the sediment that moves in the other direction [2]. Chen [23] studied high-sand-concentration currents in the floodplain, indicating that the exchange of sand content increases the sand content in the floodplain and decreases it in the main channel. Knight and Brown [24] conducted experiments to study the sediment transport in a movable bed compound channel, finding that the drag coefficient was proportional to the water depth and floodplain roughness. Tang and Knight [25] found that the bed-load rate is at the maximum when the water reaches bankfull flow; as the flow depth increases above floodplain level, the bedload rate gradually decreases. They also found that the greater the roughness of the floodplain, the lower the bedload transport rate. In addition, some studies proposed predictors for estimating the bedload rate in compound channels [26–28].

Although the flow characteristics and sediment transport in compound channels have been broadly studied, the flow characteristics and bed morphology in the compound channel between two single channels are still unknown. To fill this research gap, this study conducted flume tests for investigating the flow characteristics and bed morphology in a compound channel between two single channels.

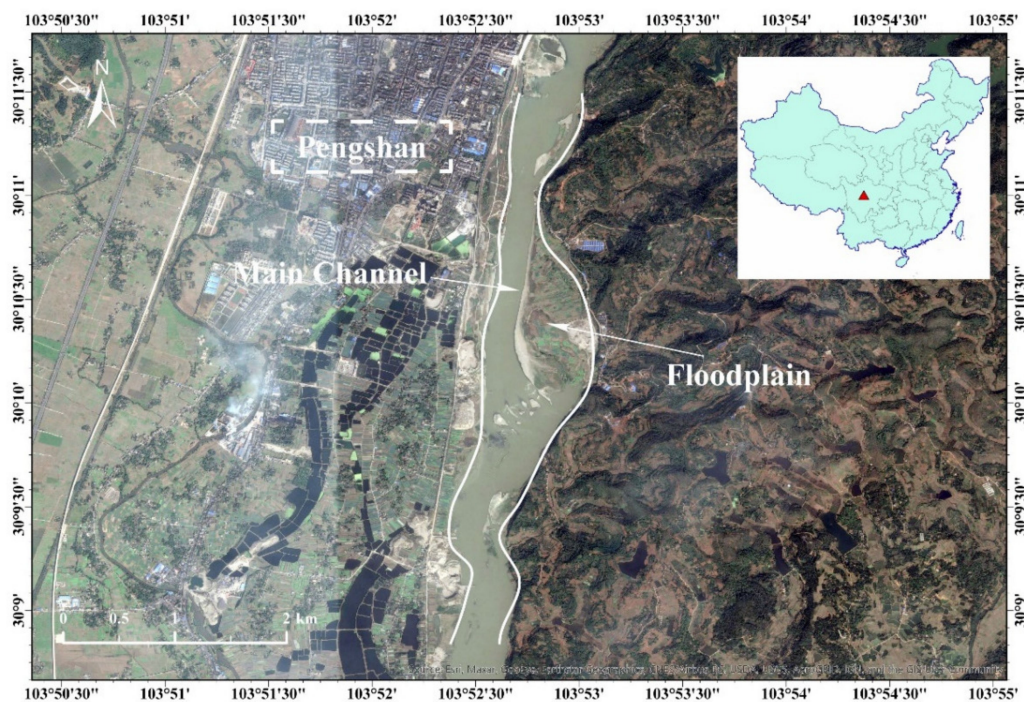


Figure 1. Abruptly widening compound channel between two single channels in the Pengshan reach of Min River (flow direction is from the North to South).

2. Experimental Setup

All experiments were conducted in a concrete flume (Figures 2 and 3) at the State Key Laboratory of Hydraulics and Mountain River Engineering, Sichuan University, China. The flume has a total length of 26 m and consists of three parts: (i) A 12 m long, 1 m wide and deep upstream single channel; (ii) an 11 m long compound channel with a main channel as wide as in (i) and two 2.1 m wide floodplains; (iii) a 3 m long, 1 m wide downstream single channel. The slopes of the main channel and floodplain for each test are 3‰. The flow discharge was measured by a rectangular thin-plate weir before a static pool at the inlet of the flume. A honeycomb flow straightener near the upstream end of the channel was used to eliminate the rotational flow component for making the incoming flow more uniform. A tailgate was installed at the end of the flume to control the water level. Downstream of the model, a sediment trap was used to collect the sediment for reuse. The main channel and the

floodplain are movable beds, constructed of uniform sand, with a median mean diameter of 0.5 mm. The main channel has concrete banks representing the channelized main channel in natural rivers. The grain-size distribution of the sediment is shown in Figure 4. The floodplain is 5 cm higher than the main channel, and the thickness of the sediment bed is 20 cm.



Figure 2. A photo of the testing flume.

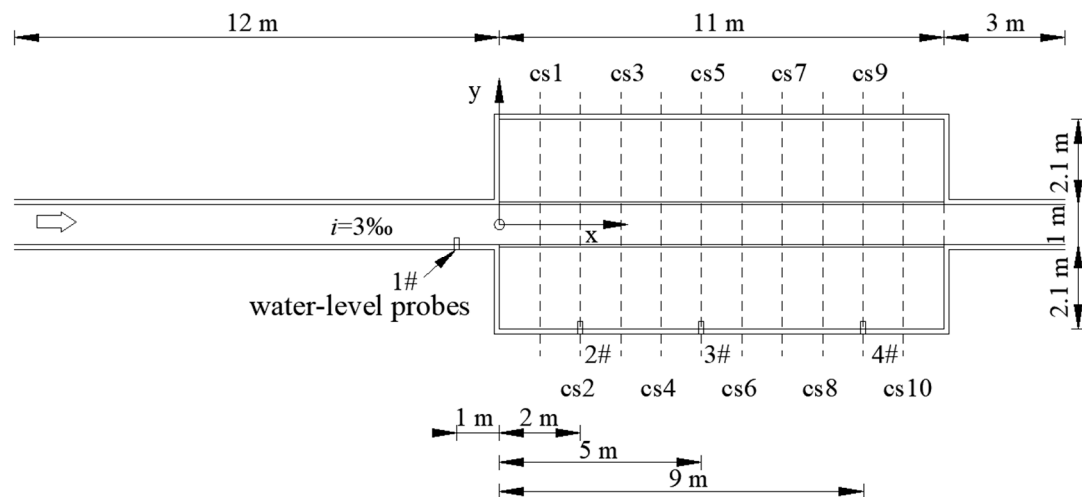


Figure 3. Sketch of the test flume.

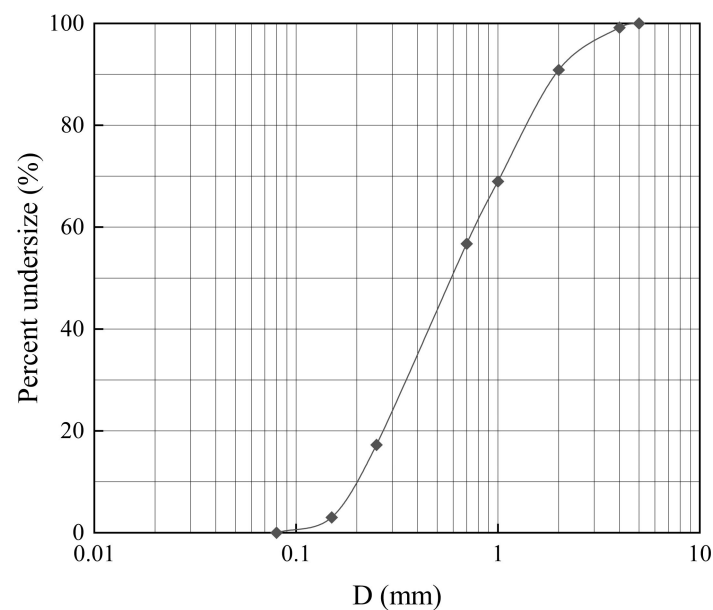


Figure 4. Grain-size distribution curve.

Seven tests were conducted with the discharge from 22 (bankfull discharge) to 45 L/s (Table 1). Each test started with an initial flat sediment bed. At the beginning of each test, the flume was filled slowly to avoid unexpected bed erosion. When the flume was filled up, the tailgate was opened slowly to ensure that the lower edge of the tailgate does not come into contact with the flow and the end of the flume is the free overfall. Four LH-1 automatic water-level probes with an accuracy of 1 mm were used to measure the water level at the upstream single channel, CS 2, CS 5, and CS 9 (Figure 3). When the sediment transport rate reached 0 and the bed was nearly unchanged (i.e., no obvious sediment deposition observed in the sediment trap) over time, the test was stopped. Thus, the experiment started under live-bed scour condition, and stopped under clear-water scour condition. After the water was slowly and carefully drained, the final bed profile was measured using a Nikon total station.

Table 1. Summary of the experimental conditions.

Test	Discharge Q (L/s)	S (‰)	D_{50} (mm)	Channel Width B (m)	Main Channel Width b (m)
1	22	3	0.5	5.2	1
2	28	3	0.5	5.2	1
3	30	3	0.5	5.2	1
4	32	3	0.5	5.2	1
5	36	3	0.5	5.2	1
6	40	3	0.5	5.2	1
7	45	3	0.5	5.2	1

3. Results and Discussion

3.1. Water Level

Figure 5 shows the final water level and bed elevation in the main channel with respect to the initial bed at $x = -1$ (upstream single channel), 2, 5, and 9 m (compound channel). Figure 5 shows that the water levels at each measurement point increase with increasing flow discharge. For each discharge, the water level in the upstream single channel is considerably lower than that in the compound channel. This is counterintuitive as, for a fixed-bed channel, the flow section widens in the compound channel, reducing the flow depth and water level in the compound channel. However, for a movable bed, the eroded sediment from the upstream single channel is deposited in the compound channel due to

the reduced velocity in the widened flow section (Figure 5). Thus, the aggraded bed of the compound channel increases the water level. Figure 5 also shows that the water level at the end of the compound channel ($x = 9$ m) is significantly higher than that at $x = 2$ and 5 m. This is because the velocity at the end of the compound channel decreases due to the water level rise before the constricted-flow section.

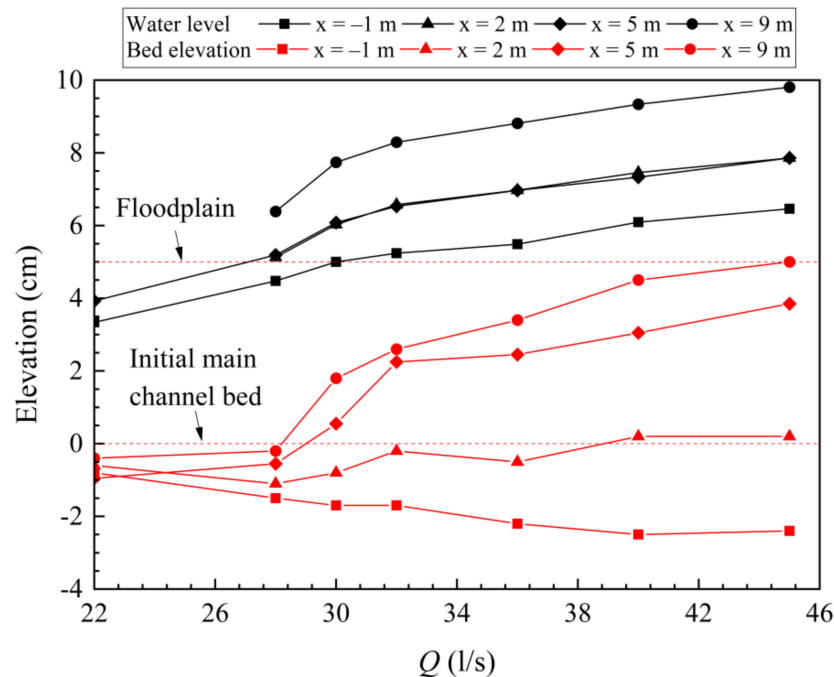


Figure 5. Dependencies of water level and bed elevation in the main channel centerline on the flow discharge at $x = -1$ m, $x = 2$ m, $x = 5$ m and $x = 9$ m.

Figure 6 shows the temporal evolution of the water level in the middle of the compound channel ($x = 5$ m) for different flow discharges. For $Q = 22$ L/s and $Q = 28$ L/s, the water level decreases over time as the discharge nears the bankfull flow. In this situation, the channel can be considered a single channel, and the water level decreases with the eroding bed level. For $Q \geq 30$ L/s, the water level increases over time as the sediment is deposited in the compound channel due to a widened channel section and reduced velocity.

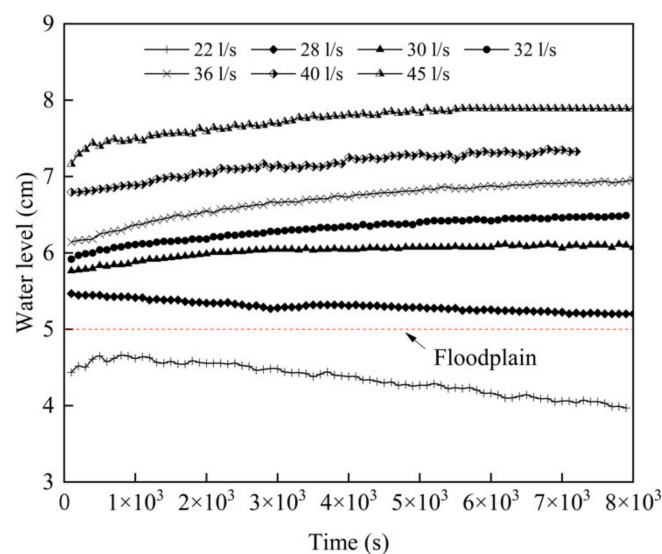


Figure 6. Temporal evolution of water level at $x = 5$ m.

3.2. Bed Profile

Figure 7 shows the longitudinal bed profile along the centerline of the main channel for different flow discharges. Figure 7 shows that the main channel bed generally degrades when $Q \leq 28$ L/s (i.e., close to the bankfull flow). As for non-bankfull discharge, the flow is completely in the main channel and continuously entrains the sediment same as that in a single channel. For $Q > 32$ L/s, the bed level in the compound channel is higher than the initial bed level. This is because the flow spills to the floodplain when the water level is above the floodplain, reducing the velocity in the main channel [25]. As a consequence, sediment deposition occurs due to the reduced flow capacity for sediment transport. The bed level generally increases downstream for $x \leq 9$ m as the water level rises downstream due to the constricted flow section in the downstream single channel. Between the compound channel and the downstream single channel ($x > 10$ m), the bed level decreases significantly due to the contraction scour [29]. The maximum deposition height is about 5 cm ($x = 7$ – 10 m), which is higher than the floodplain elevation. As this study only measures the water level at several points, the backwater curve is not obtained. However, the backwater curve is required in the future research to investigate the impacts of transition phenomena on the bed morpho-dynamic process.

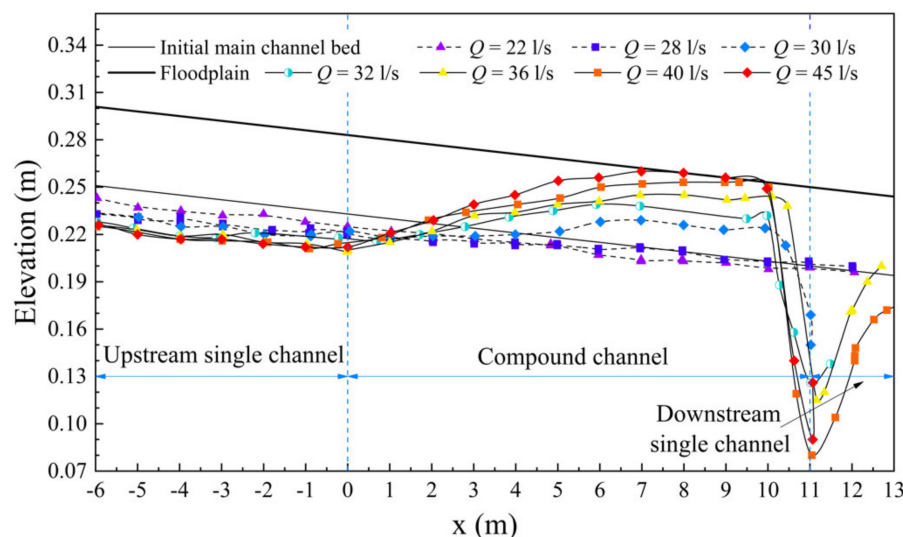


Figure 7. Longitudinal bed profile along the centerline of the main channel.

Figure 8 shows the cross-sectional bed profile in the compound channel at $x = 2$, 5, and 9 m. Figure 8 shows that the impacts of flow discharge on the cross-sectional bed profile at $x = 2$ m are smaller than those at $x = 5$ and 9 m. Although the flow section widens in the compound channel, the velocity of the flow in the main channel is still greater than in the downstream part of the compound channel. Figure 8 shows that the bed profile in the main channel at $x = 9$ m is more asymmetric than upstream, indicating that the main channel in the downstream part of the compound channel tends to migrate. However, the tendency of channel migration is inhibited by the concrete bank. For $x = 5$ and 9 m, sediment deposition occurs near the main channel. This is because the sediment eroded from the floodplain are blocked by the concrete banks and cannot enter the main channel. This difference is also caused by the flow pattern in those three areas. The experimental observations show that a backward flow forms near $x = 2$ m and disappears at $x = 5$ and 9 m. Figure 8 also shows that the floodplain is eroded for $Q \geq 36$ L/s at $x = 9$ m. This is because the bed aggrades significantly in the main channel, spilling the flow to the floodplain and increasing the eroding capacity of the flow.

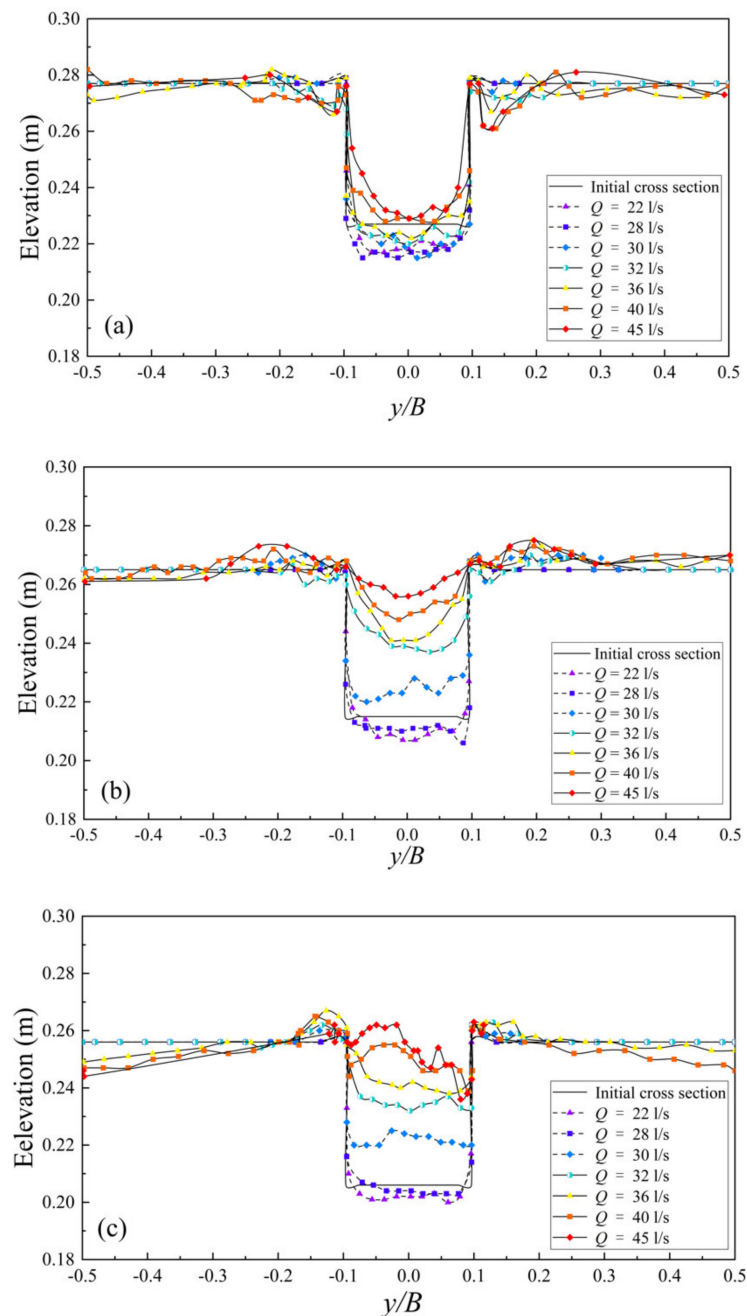


Figure 8. Cross-sectional bed profile at (a) $x = 2$ m, (b) $x = 5$ m, and (c) $x = 9$ m.

4. Conclusions

This study presented experiments investigating the flow characteristics and bed morphology in a compound channel between two single channels. Based on the experimental results, the following conclusions were reached:

The experimental results indicate that the water level at the middle of the compound channel generally increases with increasing flow discharge. For each discharge, the water level in the upstream single channel is lower than in the compound channel; the water level at the end of the compound channel is significantly higher than in the upstream compound channel. For flow discharge close to the bankfull flow, the water level at the middle of the compound channel decreases over time. For flow discharge considerably greater than the bankfull flow, the water level at the middle of the compound channel increases over time. This result implies that the flood control standard should be enhanced in

the compound channel, especially in the vicinity between the compound channel and the downstream single channel.

The main channel bed generally degrades for discharge close to the bankfull flow. When the flow discharge is considerably greater than the bankfull flow, the bed level in the compound channel is higher than the initial bed level. The bed level generally increases downstream in the compound channel. Between the compound channel and the downstream single channel, the bed level decreases significantly due to the contraction scour, indicating that attentions should be paid to the bank instability due to bed incision in this area. The maximum deposition height is greater than the floodplain elevation.

Author Contributions: W.W. did the data process, part of the results analysis and wrote the first draft. L.W. did most of the results analysis and proofread the manuscript. X.L. did the experiments and proofread the paper. R.N., X.M. proofread the paper and provided a lot of valuable advice on writing. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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