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Sediment Transport Modeling at the Bogowonto River Bend Using HEC RAS 6.6

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ABSTRACT

River bend erosion is a major concern for river engineers because it affects channel stability and navigation safety. Erosion along the outer bank and deposition along the inner bank are the primary processes responsible for the meandering pattern of rivers. This study investigates the effect of discharge variations on scour depth in a meandering reach of the Bogowonto River using numerical modeling with HEC-RAS 6.6. Simulations were carried out for six discharge scenarios corresponding to return periods of 2,5, 10, 20, 50, and 100 years (Q_2, Q_5, Q_{10}, Q_{20}, Q_{50}, and Q_{100}). The historical rainfall data collected from 2002 to 2021. Limantara Unit Hydrograph used for rainfall-runoff modelling. The HEC-RAS simulation results of the 2-year return period (Q_2) reveal that sedimentation occurs at five points along the Bogowonto River bend in Purworejo District. In particular the greatest accumulation occurred at the apex of the bend (STA 17), where the bed sediment thickness reached 4.175 m at the Q100 discharge. The simulation results show a uniform sedimentation pattern across the entire bend cross-section, likely due to model limitations that prevent detailed representation of cross-flow patterns.

1. Introduction

In river bends, unique flow mechanisms can be investigated using both physical and numerical approaches. Numerous experimental and laboratory studies have been conducted to analyze flow characteristics in curved channels. Secondary flow develops in a helical pattern perpendicular to the primary flow, moving toward the outer bank in the upstream section of a bend and toward the inner bank in the downstream section. The presence of this secondary flow drives sediment redistribution and transport, forming distinctive bed and bank profiles. Understanding this flow pattern is essential for predicting river bend morphology and evolution [1].

Secondary currents are unique to open-channel bends and consist of two distinct components: a dominant helical motion in the channel core and a weaker countercurrent circulation near the outer bank. The latter plays an important role in erosion processes along the outer bend and results from the combined effects of centrifugal force and crossflow turbulent pressure. Although this outer-bank circulation is relatively weak and difficult to measure, it tends to be strongest in sharply curved bends. Despite its subtlety, it has a stabilizing influence on outer-bank erosion and enhances mixing processes within this region [2].

Erosion damage along river bends can cause significant socio-economic and environmental problems, particularly in densely populated floodplain areas. Progressive bank erosion may lead to land loss, displacement of residents, economic disruption, and ecological degradation [3]. Such erosion-related issues have been reported in several major rivers, including the Yangtze River [4], the Mekong River [5], the Powder River in the United States [6], and the Brahmaputra River in India [7].

Bank erosion is a combined outcome of three main processes: fluvial erosion, mass erosion, and mass failure [8]. Fluvial or hydraulic erosion refers to the detachment and removal of individual cohesive particles or aggregates at the sediment–flow interface under the shear action of the flow [9]. Numerical simulations reveal that flow characteristics in bends differ significantly from those in straight channels. In straight reaches, the maximum velocity typically occurs along the channel centerline; however, in bends, this high-velocity core shifts toward the outer bank. Consequently, erosion and sedimentation risks are greater in curved sections of rivers [10].

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Two main mechanisms can explain bank erosion in river bends. First, in sharply curved bends, high flow discharges tend to shift the core of maximum velocity away from the outer bank, reducing boundary shear stress and fluvial erosion during peak flow. Second, bank failure may be triggered by the combined effects of pore-water pressure and hydrostatic pressure that develop during the rise and fall of multipeak flow events [11]

Laursen-Copeland equation

Sediment transport involving bed-material gradation is commonly analyzed using the Laursen–Copeland equation, which predicts sediment transport rates in rivers with non-uniform bed materials. The Laursen–Copeland equation is one of the most widely applied empirical models in river engineering and sedimentology for estimating suspended sediment transport rates. This model was developed based on observations of the relationship between flow characteristics and sediment concentration in moving water. The fundamental theory underlying the equation is the balance between the turbulent lift force, which suspends sediment particles in the flow, and the gravitational settling force, which causes them to deposit.

The original Laursen equation was later modified by Copeland and other researchers to improve its applicability in practical river engineering. It has since been used in various applications, including hydraulic structure design, reservoir sedimentation analysis, and river basin management [12]. The model provides a quantitative framework for understanding sediment transport dynamics, which is crucial for the design of hydraulic infrastructure and effective water resource management. In modern practice, the Laursen–Copeland equation, as implemented in HEC-RAS software, serves as a standard approach for simulating sediment transport processes involving heterogeneous sediment gradations.

Meyer Peter-Muller equation

The Meyer-Peter Müller (MPM) equation is one of the most widely used formulas in sediment transport theory, particularly for calculating bedload transport in river flows [13]. The fundamental concept of this equation is that sediment transport occurs when the bed shear stress (τ) exceeds the critical shear stress (τc) required to initiate particle motion. To express this relationship, a nondimensional parameter known as the Shields parameter (θ) is used, representing the ratio between the bed shear force and the submerged weight of sediment particles. When θ exceeds the critical value θc (approximately 0.047 for non-cohesive sediments), sediment motion begins, resulting in bedload transport [14]. The MPM equation was originally developed by Meyer-Peter and Müller (1948) based on a series of laboratory experiments using materials ranging from coarse sand to gravel.

Initially, the MPM equation was formulated to predict bedload transport in open-channel flows with relatively uniform sediment size distributions. However, in natural rivers, bed materials are rarely uniform; they typically exhibit grain-size variation, known as bed material gradation. Under such conditions, sediment transport becomes more complex due to interactions among particles of different sizes [13].

Building on this theoretical framework, this study aims to analyze the effects of groyne installation on river erosion and sedimentation dynamics. The simulation results are expected to provide a scientific basis for planning groyne configurations that minimize bank erosion and enhance sediment deposition in targeted river sections.

2. Methods

This research was conducted in two main stages: river cross-section data collection and field observation. The data collection sites were located in the downstream section of the Bogowonto River, specifically in the villages of Bapangsari, Bugel, Bagelen, Jenar Wetan, Purwosari, and Purwodadi, situated in Purworejo Regency, Central Java (Figure 1). The subsequent stage involved calculating design rainfall and river flood discharge, followed by testing soil gradation and river geometry using the HEC-RAS application. Soil sampling was conducted to analyze the distribution of sediment gradation, which served as input data for the HEC-RAS model.

The river section data is shown in Figure 2. Design flood discharges calculation is based on available rainfall data for 20 years, from 2002 to 2021 [15]. The maximum regional rainfall data is presented in Table 1. The rainfall-runoff process conducted by Limantara Unit Hydrograph. The result of flood hydrograph with several return period is shown in Figure 3.

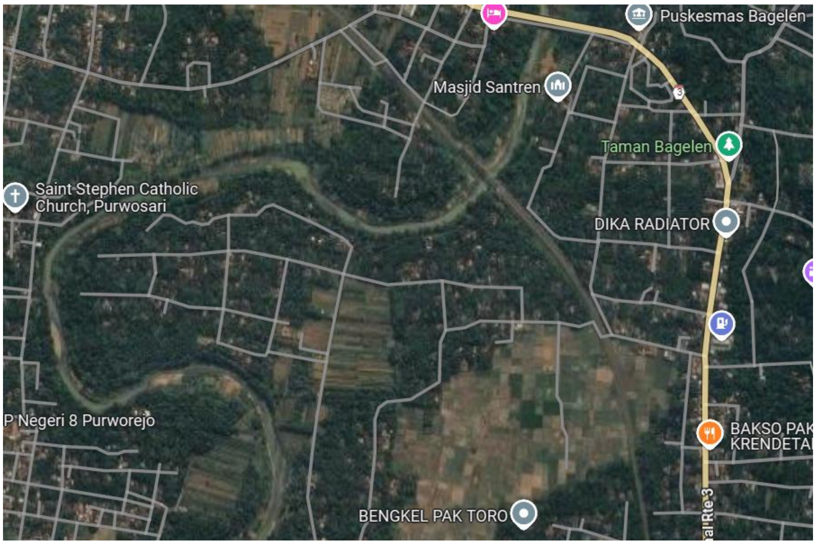

Figure 1. Research Location in Bogowonto River

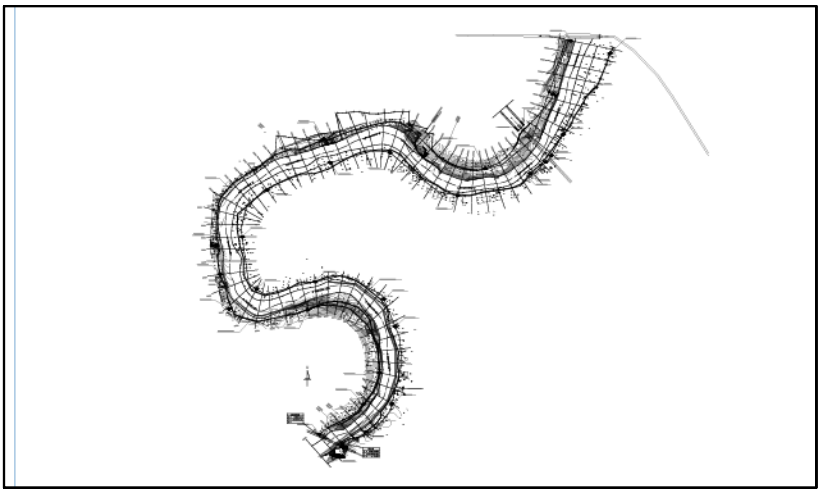
Figure 2. River Geometry Data [15]

Table 1. Maximum Area Rainfall Data

Year	Rainfall (mm)	Year	Rainfall (mm)
2002	62	2012	77
2003	128	2013	87
2004	263	2014	80
2005	124	2015	89
2006	102	2016	166
2007	72	2017	161
2008	144	2018	84
2009	95	2019	189
2010	81	2020	155
2011	57	2021	110

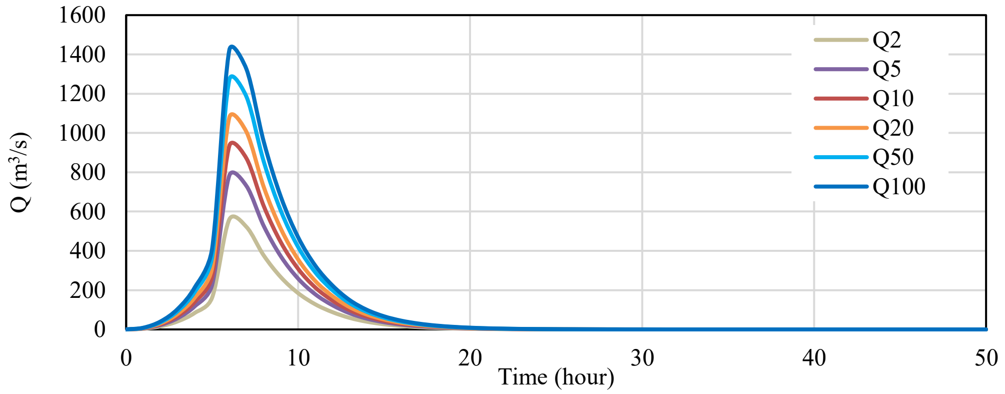

Figure 3. Annual Flood Discharge with HSS Limantara of Bogowonto River [15]

The sediment transport simulation was carried out in the HEC-RAS program using river cross-section data from several measurement stations.

Cliff Erosion on River Bends

River bends represent a distinctive hydraulic phenomenon that requires careful study, as erosion and deposition frequently occur in these sections [16]. The geometry of the bend is an important factor to consider because it significantly influences flow structure, velocity distribution, erosion processes, and channel migration [17].

Sediment Transport Simulation with HEC-RAS

HEC-RAS is a hydraulic modeling software used to simulate water flow in open channels, rivers, and flooded areas. To model sedimentation using HEC-RAS, several data required as follows: (1) River geometry data, (2) Sediment data, and (3) define the boundary condition.

The geometry used in modeling is river topography data in the form of cross-sections and longitudinal sections. The sediment gradation was obtained through appropriate sediment sampling methods for bed sediments at Bogowonto river that has been obtained is inputted in the Define Bed Gradation menu. The boundary condition in this modeling simulation is the annual discharge from Q2 to Q100. The sediment boundary condition is sediment load.

Analysis of Sediment Transport and River Morphological Changes and the magnitude of morphological changes that can be visualized in the form of graphs and numbers [18].

For available soil and cross-section data, flow modeling using HEC-RAS is also recommended. The next step is to select a river with preliminary sedimentation studies, specifically focusing on the analysis of floating sediment concentrations in the designated area [19].

3. Results

The results of the annual flood calculations can be presented in Table 2.

Table 2. Annual Flood Calculation

Flood on return period	
Q_2	560 m^3/s
Q_5	784 m^3/s
Q_{10}	935 m^3/s
Q_{20}	1079 m^3/s
Q_{50}	1272 m^3/s
Q_{100}	1422 m^3/s

In this study, the analysis was conducted by simulating river flow using the HEC-RAS software application, incorporating riverbed soil grain gradation values and simulations with quasi-steady flow conditions. The simulation results provided the maximum sediment deposition value found at the river bend and the maximum scour value. In this simulation, a 2-year return period discharge was applied under steady flow conditions. The HEC-RAS program simulation conducted from STA 14 to STA 18 produced results in the form of flow velocity distribution and a comparison between the original riverbed profile and the modified profile after applying the discharge and grain gradation data.

4. Discussion

Simulations with HEC-RAS were conducted for several stations. After performing simulations using six annual return period discharges with values of Q_2 = 560 m^3/s, Q_5 = 784 m^3/s, Q_{10} = 935 m^3/s, Q_{20} = 1079 m^3/s, Q_{50} = 1272 m^3/s, and Q_{100} = 1422 m^3/s, the results of the water flow velocity analysis showed variations in velocity values across each river segment.

In the simulation conducted with Q_2 = 560 m³/s, Q_5 = 784 m³/s, Q_{10} = 935 m³/s, Q_{20} = 1079 m³/s, Q_{50} = 1272 m³/s, and Q_{100} = 1422 m³/s, under conditions without groyne structures at STA 411, the results showed that the water flow velocity at a Q100 discharge of 1422 m³/s was higher, with a maximum velocity of 3.05 m/s, compared to the discharges of Q_2, Q_5, Q_{10}, Q_{20}, and Q_{50}.

The simulation results of the flow velocity distribution at STA 14 and STA 18 are shown in Figure 4 and Figure 5.

The recapitulation of the flow velocity distribution at the bends at stations 14 to 18 is presented in Table 3.

The sediment transport and sedimentation analysis was conducted only in the bend area, specifically between STA 18 and STA 14, where active sediment transport occurs. The analysis was based on flow simulation results using hydrograph discharges with return periods of 2, 5, 10, 20, 50, and 100 years to observe the river's response to flood events. Changes in riverbed elevation at each cross-section are presented in Figure 6 and Figure 7.

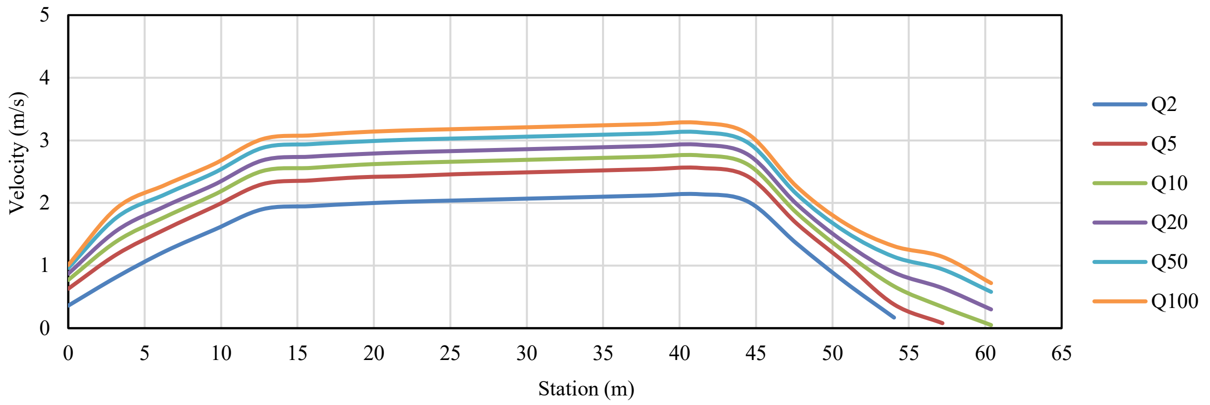

Figure 4. Flow velocity distribution at STA 14

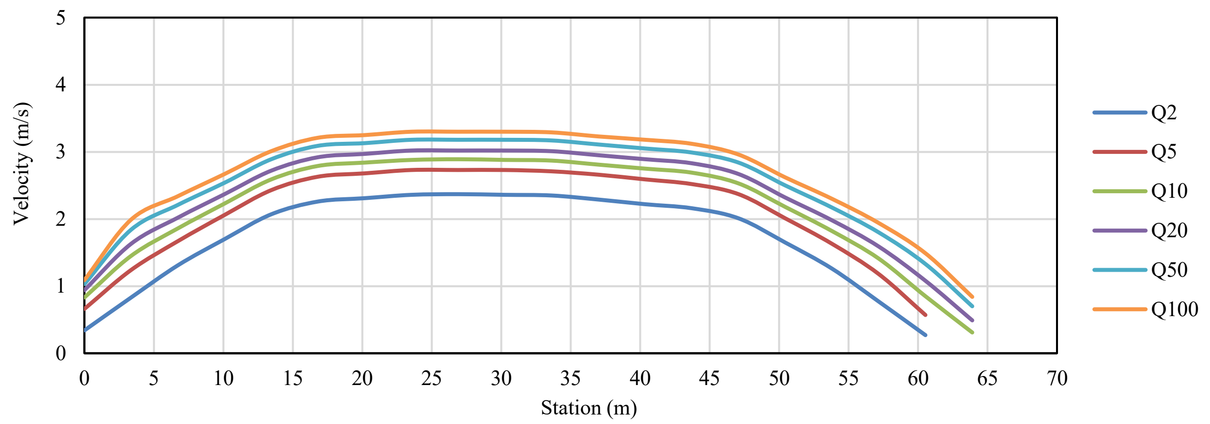

Figure 5. Flow velocity distribution at STA 18

Table 3. Flow Velocity Distribution in Bogowonto River Bends

Flood discharge	Maximum velocity (m/s)				
	Sta-14	Sta-15	Sta-16	Sta-17	Sta-18
Q_2	2.08	2.37	2.35	2.52	2.60
Q_5	2.56	2.73	2.72	2.91	3.09
Q_{10}	2.76	2.89	2.89	3.06	3.33
Q_{20}	2.93	3.02	3.04	3.06	3.55
Q_{50}	2.93	3.02	3.04	3.06	3.55
Q_{100}	3.26	3.30	3.35	3.45	4.00

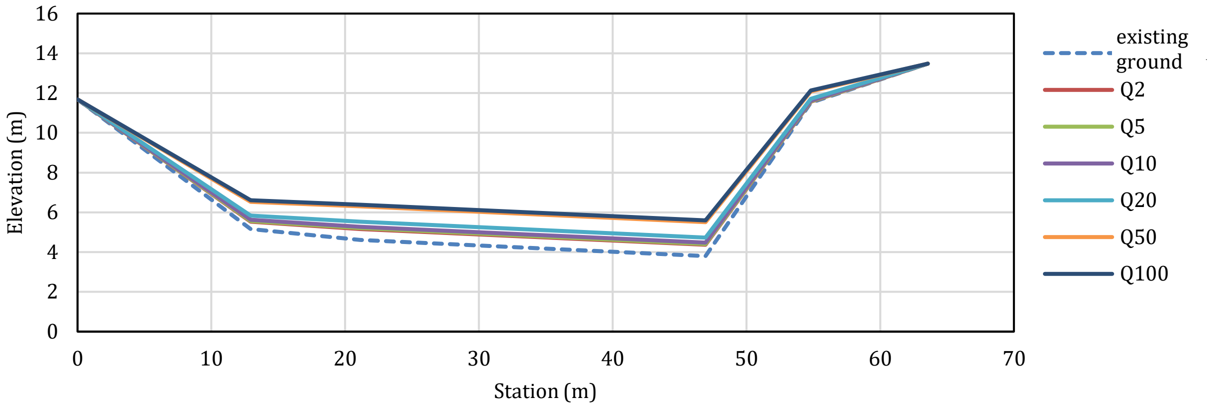

Figure 6. Changes in Riverbed Elevation at STA 14

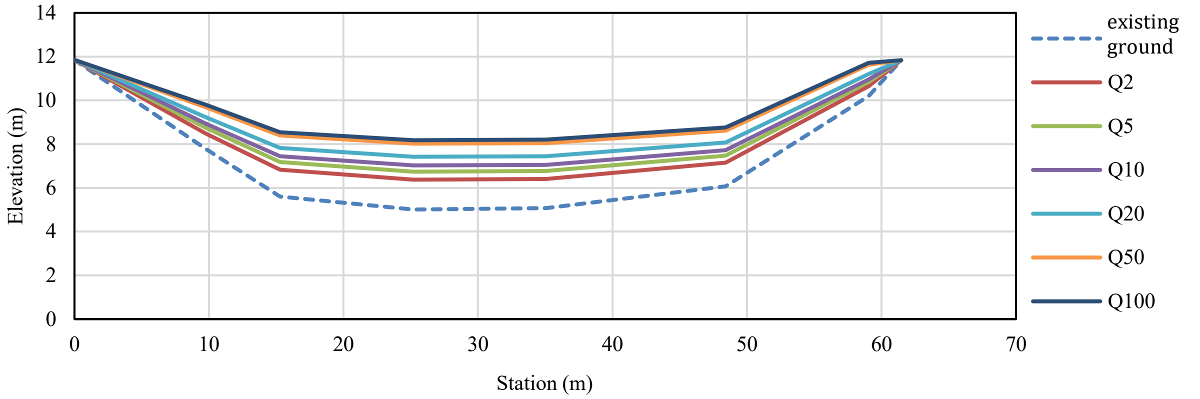

Figure 7. Changes in Riverbed Elevation at STA 16

Based on the sediment transport simulation results presented in Figure 6 and Figure 7, it can be observed that the riverbed experienced sedimentation or aggradation across the entire cross-section around the bend. This is indicated by the consistent increase in riverbed elevation after simulations using hydrograph discharges compared to the initial (native soil) condition. The amount of sedimentation also increases with the discharge return period, with the most significant sedimentation occurring at the 100-year return period.

Table 4. Cumulative Recapitulation of Riverbed Elevation Changes

Flood discharge	Riverbed sedimentation (m)				
	Sta-14	Sta-15	Sta-16	Sta-17	Sta-18
Q_2	0.570	0.824	1.365	1.552	1.028
Q_5	0.607	1.165	1.729	2.369	1.098
Q_{10}	0.678	1.461	2.016	2.911	1.415
Q_{20}	0.929	1.990	2.412	3.308	1.223
Q_{50}	1.707	2.830	3.010	3.988	1.466
Q_{100}	1.797	3.053	3.168	4.175	1.487

Table 4 presents the cumulative changes in riverbed elevation, as indicated by the difference from the original riverbed elevation. From these data, the sediment deposition pattern along the analyzed bend can be more clearly observed. As the flow enters the beginning of the bend at STA 18, the sedimentation rate remains relatively low at 1.487 meters for Q100. However, as the flow reaches the bend peak at STA 17, there is a significant increase in deposition, with an accumulated thickness of up to 4.175 meters, followed by STA 16 with a sedimentation thickness of 3.1676 meters at Q100. This high accumulation occurs because STA 17 is located precisely at the bend peak, which is a zone of flow transition and potential turbulence. During the simulation, this area was identified as a deceleration zone, where the flow loses energy, causing sediment materials carried from upstream to settle, resulting in the greatest accumulation at that location. After the flow passes the bend peak, the sedimentation rate decreases again at STA 15 and STA 14, where the flow begins to exit the bend.

The simulation results in this study indicate a discrepancy with the theoretical understanding of morphological processes in river bends. Theoretically, flow in a river bend generates a secondary (helical) flow, which results in higher flow velocities along the outer side of the bend. This condition should lead to erosion or scour on the outer bend and sedimentation on the inner bend.

5. Conclusions

Increasing the return period discharge consistently raises the maximum flow velocity at the Bogowonto River bend. The highest velocity occurs at the Q_{100} discharge, reaching 4.00 m/s at STA 18, compared to 2.60 m/s at the Q_2 discharge.

The increase in discharge also elevates the water surface level along the river and enhances the potential flow energy, particularly in the outer bend area. This corresponds with the velocity distribution results, which show a shift in the velocity peak toward the outer side of the bend.

The sediment transport modeling results indicate that the entire cross-section at the bend (STA 18–STA 14) experienced an increase in riverbed elevation due to sedimentation. The greatest accumulation occurred at the apex of the bend (STA 17), where the bed sediment thickness reached 4.1753 m at the Q100 discharge, while the downstream section of the bend (STA 14) exhibited smaller sedimentation of 1.7972 m.

Theoretically, river bends typically experience erosion on the outer bank and sedimentation on the inner bank due to the influence of secondary flow. However, the simulation results in this study show a uniform sedimentation pattern across the entire bend cross-section, likely due to model limitations that prevent detailed representation of cross-flow patterns.

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