Flume experiments of deposition rate on foreset of silty delta relative to hydrographic patterns

SUZUKI Taro[1], ENDO Noritaka[2]

(1. Department of Earth and Environmental Sciences, Kanazawa University, Kanazawa 920-1192, Japan; 2. School of Natural System, Kanazawa University, Kanazawa 920-1192, Japan)

Abstract: Foreset profiles of deltaic topography change corresponding to hydraulic conditions, and are influenced by water discharge and change rates of water discharge. To investigate the correlation between the transition of deposition rates on the foreset and the change rate of water discharge of temporary waxing and subsequent waning flows, we perform experiments on silty deltas that developed under several different hydrographic patterns. The findings are as follows: (1) Under flows with constant discharge, the deposition rate on the foreset was low at high water discharge and high at low water discharge because the separated flow became vigorous at high water discharge and prevented sediment supply onto the foreset. If the water discharge is not constant, the deposition rate shifted concurrently with water discharge only at extremely low change rate. (2i) In a waxing flow at low (but not extremely low) increase rate, the deposition rate gradually decreased with some time lag. (2ii) In the case of high increase discharge, intense erosion on the topset caused by rapid waxing made a large amount of silt move onto the foreset and the deposition rate temporary increased. (3) With ample time after waning stage, the deposition rate recovered to that at constant low water discharge in all runs. However, the transitional processes depended on not only waning rate but also waxing rate at before waning stage. (3i) In the case of high decrease rate of water discharge, the deposition rate abruptly decreased regardless of increase rate. (3ii) Even in the case of low decrease rate of water discharge, if the increase rate before waning stage was high, the deposition rate abruptly decreased. (3iii) Only in the case where both the increase rate and the decrease rate were low, deposition rate gradually increased.

Key words: delta system; hydrographic patterns; deposition rate on the foreset; flume experiments; change of sediment flux

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1 Introduction

Deltaic topographies (e.g., deltas at river mouths or unit bars in rivers) advance downstream because of the sediment supplied to the foreset; the foreset profile is determined by various parameters such as flow velocity on the topset (Jopling, 1965; Kojima and Yokokawa, 1997), sediment supply rate (Okazaki et al, 2004), sediment transport modes (Okazaki et al, 2004; Reesink and Bridge, 2007, 2009), and sediment types (Jopling, 1965; Kostic and Parker, 2003). Suzuki and Endo (2010) performed flume experiments by using silt in which a water discharge was constant during each run, and discovered that its foreset profile trend differed from that of sand in relation to water discharge. If the supply rate of silt was relatively high, the foreset gradient was steep at relatively high water discharge; however, it was gentle at relatively low water discharge (Suzuki and Endo, 2010). Suzuki and Endo (2011) also conducted experiments in which the water discharge was varied during each run to investigate the

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Corresponding author: SUZUKI Taro, School of Natural Science and Technology, Kanazawa University Kakuma-nachi, Kanazawa, Ishikawa, 920-1192, Japan, E-mail: tarosa@stu.kanazawa-u.ac.jp

dependence of the foreset profile on the change rates of water discharge (rates of acceleration or deceleration). They obtained a new delta profile with a gradient change point at the middle of the foreset, which was not observed in the previous studies of constant water discharge (Suzuki and Endo, 2010). In this study, we measured the deposition rate on the foreset in experimental runs with various water discharges to discuss their tendency in relation to the change rates of water discharges.

2 Materials and methods

We used a flume that was 1 m long, 15 cm deep, and 2.7 cm wide and silt sediments with a mean density of 2.2 g·cm^{-3}, median diameter of 37.8 μm, and mode diameter of 48.8 μm, which was identical to Suzuki and Endo (2010, 2011). The mixtures of silt and water were supplied to the upstream area of the flume by a pump (Fig.1). We set the sediment supply rate at 3.0 g·min^{-1} to match Suzuki and Endo (2011). Water discharge was regulated through a flow controller. We examined seven hydrographic patterns by varying the discharge between 200 and 600 mL·min^{-1} in addition to runs of constant water discharge (Table 1). The combinations of increase rates (rates of acceleration) and decrease rates (rates of deceleration) were as follows: (EL-EL) +10 and −10 mL·min^{-2}; (L-H) +20 and −800 mL·min^{-2}; (L-L) +20 and −20 mL·min^{-2}; (H-H) +800 and −800 mL·min^{-2}; and (H-L) +800 and −20 mL·min^{-2} (Table 1). The initial topography was formed by exerting a water discharge of 200 mL·min^{-1} to provide ample time for the delta to maintain a stable state. We repeated several experimental runs for specific hydrographic patterns, although typical results were shown by only exemplifying one run for each condition described in the subsequent section.

Table 1 Experimental conditions showing change rate of water discharge

	Waxing stage		Waning stage	
	waxing rate (mL·min^{-2})	duration (min)	waning rate(mL·min^{-2})	duration (min)
EL-EL	+10 (extremely low rate)	40	–10 (extremely low rate)	40
L-H	+20 (low rate)	20	–800 (high rate)	0.5
L-L	+20 (low rate)	20	–20 (low rate)	20
H-H	+800 (high rate)	0.5	–800 (high rate)	0.5
H-L	+800 (high rate)	0.5	–20 (low rate)	20

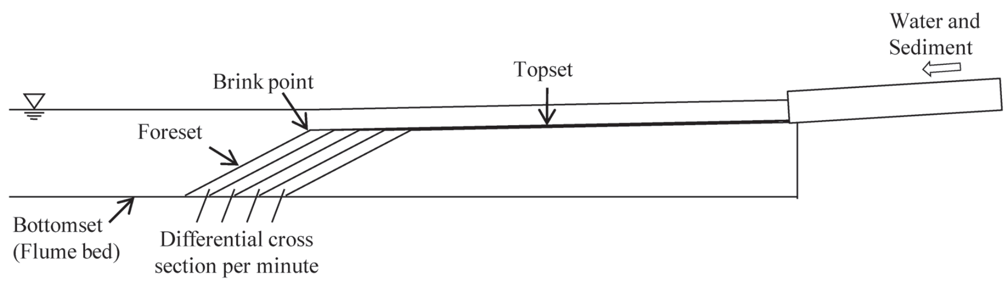

Fig.1 Schematic of experimental apparatus

The deposition rate on the foreset was defined as the product of the differential cross section per minute and the flume width. The differential cross section was measured using image processing software by subtracting two sequential photographs (Fig.1).

3 Results

3.1 Constant water discharge (200 and 600 mL· min^{-1})

In this case, the deposition rate on the foreset was almost constant (Fig.2) indicating that the sediment balance realized quasi-equilibrium states. However, the deposition rate on the foreset was inversely proportional

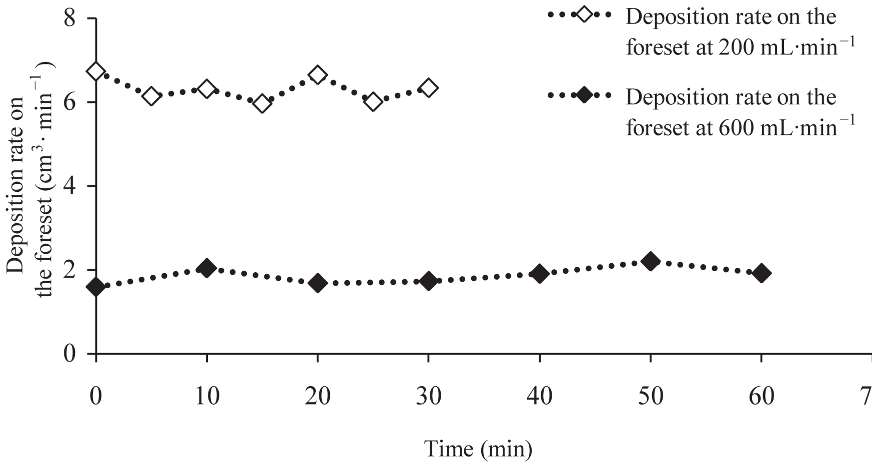

Fig.2 Deposition rates on foreset at constant water discharges

to the discharge, thus lower at higher water discharge (600 mL·min^{-1}) and higher at lower water discharge (200 mL·min^{-1}) (Fig.2). This measurement agrees with the qualitative observation that separated flow became vigorous at higher water discharge and an amount of grains transported by separated flow downstream far from the foreset increased; therefore, the sediment supply rate onto the foreset decreased (Suzuki and Endo, 2010, 2011).

3.2 Run EL-EL (extremely low increase and decrease rates)

The deposition rate on the foreset decreased as the discharge increased and increased as the discharge decreased (Fig.3). This transition was reasonable for the results of the constant water discharge runs. It was observed that the water depth on the topset increased with increasing discharge and decreased with decreasing discharge. However, the sediment balance on the topset was considered to be in a quasi-equilibrium state because the change rate of the discharge was minimal, which explains the minimum deposition rate corresponding well to the peak water discharge almost without any time lag.

The dominant sediment transport mode on the foreset shifted from laminar density currents to grain flows, and the foreset profile changed from a gentle slope with tangential contact between foreset and bottomset to a steep slope with angular contact when the discharge increased and vice versa. The delta is advanced by progradation throughout the run. It could

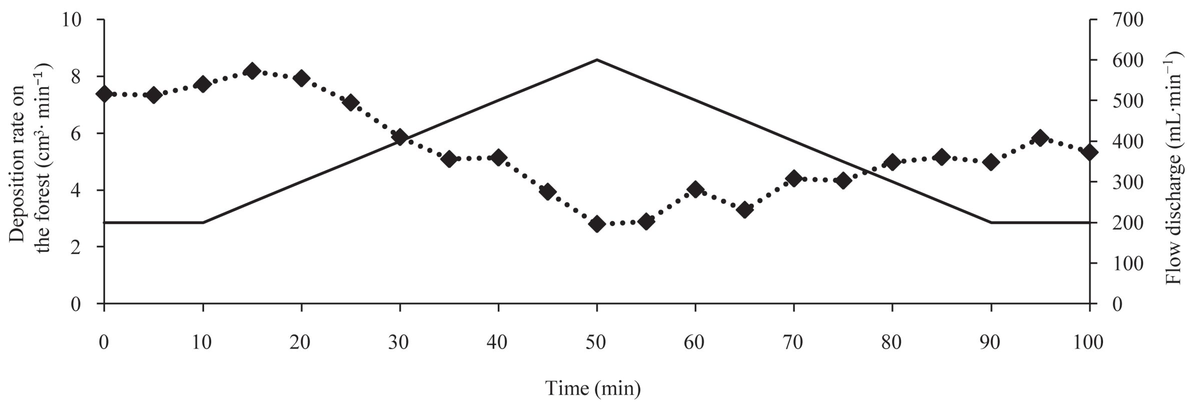

Fig.3 Deposition rates on the foreset of Run EL-EL are represented by dotted lines; solid lines represent water discharge. At the early stage, the deposition rate was somewhat higher than that of other runs, which was considered to be due to imperfect pump control. Although the pump was occasionally unstable at the early stage of the run, the qualitative interpretation was unaffected.

be concluded that the foreset shape, sediment transport modes on the foreset and the deposition rate on the foreset change by realizing a metastable state that corresponds to the water discharge when its change rate was extremely low.

3.3 Run L-L (low increase and decrease rates)

At the waxing stage, when the water discharge reached to the maximum (600 mL·min^{-1}), the deposition rate on the foreset did not take the minimum, unlike Run EL-EL (Fig.4a). The topset was in a non-equilibrium state; the extra sediment was supplied by the topset erosion onto the foreset. The process of delta development was a hybrid of progradation and backstepping probably because the progradation speed toward downstream was exceeded by the migration speed of depocenter toward upstream on the foreset because of the changes in the transport mode from laminar density currents to grain flows. Thus, the process of delta development and the trend of transition of the deposition rate on the foreset can be affected by increase rates of water discharge.

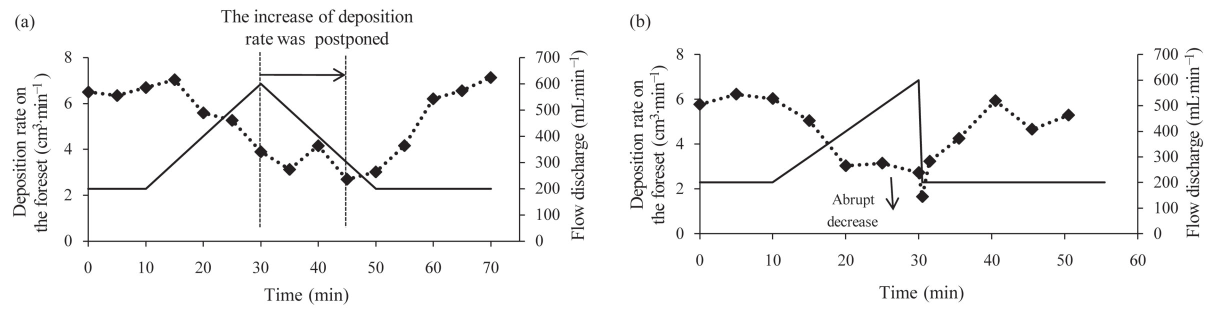

Fig.4　Deposition rates on the foreset of (a) Run L-L and (b) Run L-H (dotted lines). Solid lines indicate water discharge.

At the waning stage with a low decrease rate of −20 mL·min^{-2}, the transition of the foreset profile showed tendencies similar to those of Run EL-EL (−10 mL·min^{-2}); the foreset slope became gentle (Fig.3, Fig.4a). However, the increase in deposition rate was postponed to the moment the discharge began to decrease. This suggests that the sediment balance at the topset was in a non-equilibrium state at the rate of ±20 mL·min^{-2}, but achieved a quasi-equilibrium state at the change rate of ±10 mL·min^{-2} (Run EL-EL).

The transport modes on the foreset and the foreset profile changed concurrently with the water discharge; that is, the foreset slope steepened and the transport modes changed from laminar density currents to grain flows when the discharge increased and vice versa (Suzuki and Endo, 2011).

3.4 Run L-H (low increase and high decrease rates)

The trend at the waxing stage was similar to that of Run L-L. At the waning stage with a high decrease rate of −800 mL·min^{-2}, the deposition rate on the

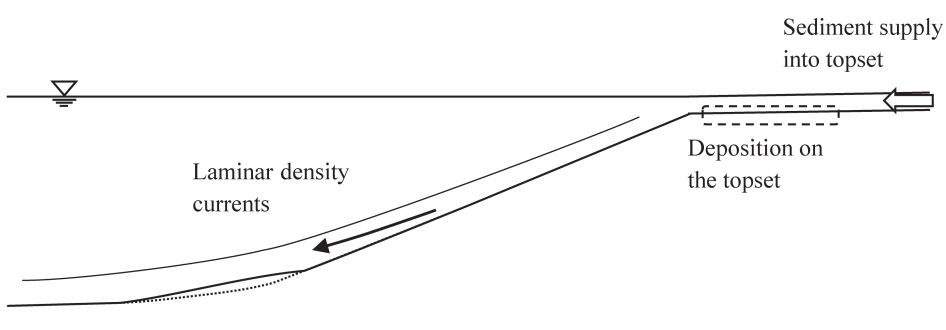

Fig.5　Schematic representation of Run L-H at discharge reached its minimum (200 mL·min^{-2})
Laminar density currents transported sediments preferentially to the lower part of the slope resulting in a low-angle, gentle slope.

foreset decreased abruptly (Fig.4b), which differed from the expected result observed in the case of constant discharge. This contrast can be explained by the sediment supplied from upstream preferentially depositing on the topset because of the increase in depth by erosion during waxing; therefore, the quantity of sediment passing through the brink point (Fig.1) decreased.

After the discharge decreased to 200 mL·min^{-1} and was kept constant, the delta developed by aggradation of the sediments transported by laminar density currents passing through the upper steep part of the slope, settling on the lower part, and creating a gentle slope covering the contact point between the foreset and the bottomset (Suzuki and Endo, 2011) (Fig.5).

3.5 Run H-H (high increase and decrease rates)

In the waxing stage, the deposition rate on the foreset increased abruptly (Fig.6a) because the intense erosion on the topset caused by rapid waxing made a large amount of silt move to the downstream area owing to turbidity currents denser than laminar density currents at 200 mL·min^{-1} onto the foreset (Fig.7a: the photo and schematic representation are actually from Run H-L, whereby the condition at the waxing stage was same as that of Run H-H.)

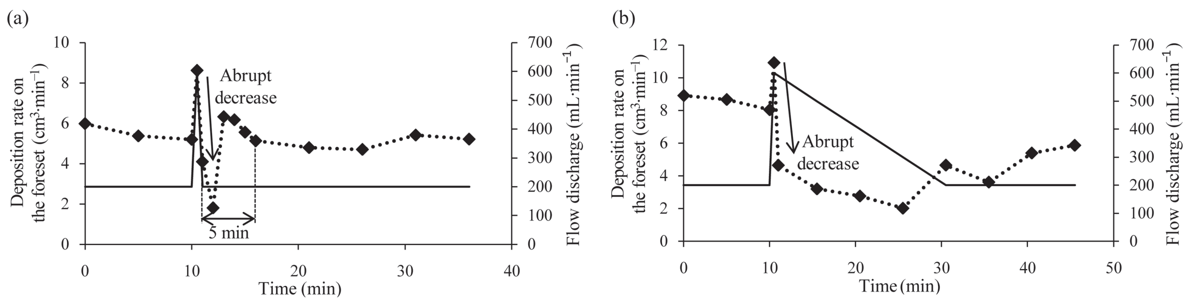

Fig.6 Deposition rate on the foreset of (a) Run H-H and (b) Run H-L.
Dotted lines indicate deposition rates and solid lines indicate water discharge.

In the waning stage, the deposition rate on the foreset once abruptly decreased (Fig.6a). However, after the discharge reached 200 mL·min^{-1}, the deposition rate recovered to a rate similar to that of the initial stage (before the increase and the decrease of the discharge), which occurred in approximately 5 min (Fig.6a). The foreset shape did not considerably change, because the foreset shape changed more slowly than the discharge and the duration of changing discharge was extremely short in this case.

3.6 Run H-L (high increase and low decrease rates)

The change rate of the discharge at the waxing stage was same as that of Run H-H and the transitions of the topographies and the sedimentary processes were also identical. After the deposition rate on the foreset increased temporarily at the waxing stage, the deposition rate at the waning stage (−20 mL·min^{-2}) decreased rapidly just after the discharge began to wane because of dense turbidity currents. These turbidity currents were caused by an increase in sediment flux due to a long duration of topset erosion and were denser than those at waxing stage of Run H-H. The dense turbidity currents passed through the foreset and reached to the bottomset, resulting in aggradation (Fig.7b). The deposition rate on the foreset continued to decrease as the discharge decreased, because the transport mode changed from dense turbidity currents to grain flows on the foreset. The diminished sediment concentration caused by less intense erosion on the topset intensified the transport by the separated flow that resulted in an increased amount of grains transported downstream far from the foreset and smaller amount of sediment supply onto the foreset (Suzuki and Endo, 2011) (Fig.7c). A new, small delta with a steep slope formed on the upper part of the foreset of the large existing delta and proceeded (Fig.7c). When the water discharge decreased further, the deposition rate on the foreset increased in a manner similar to that of

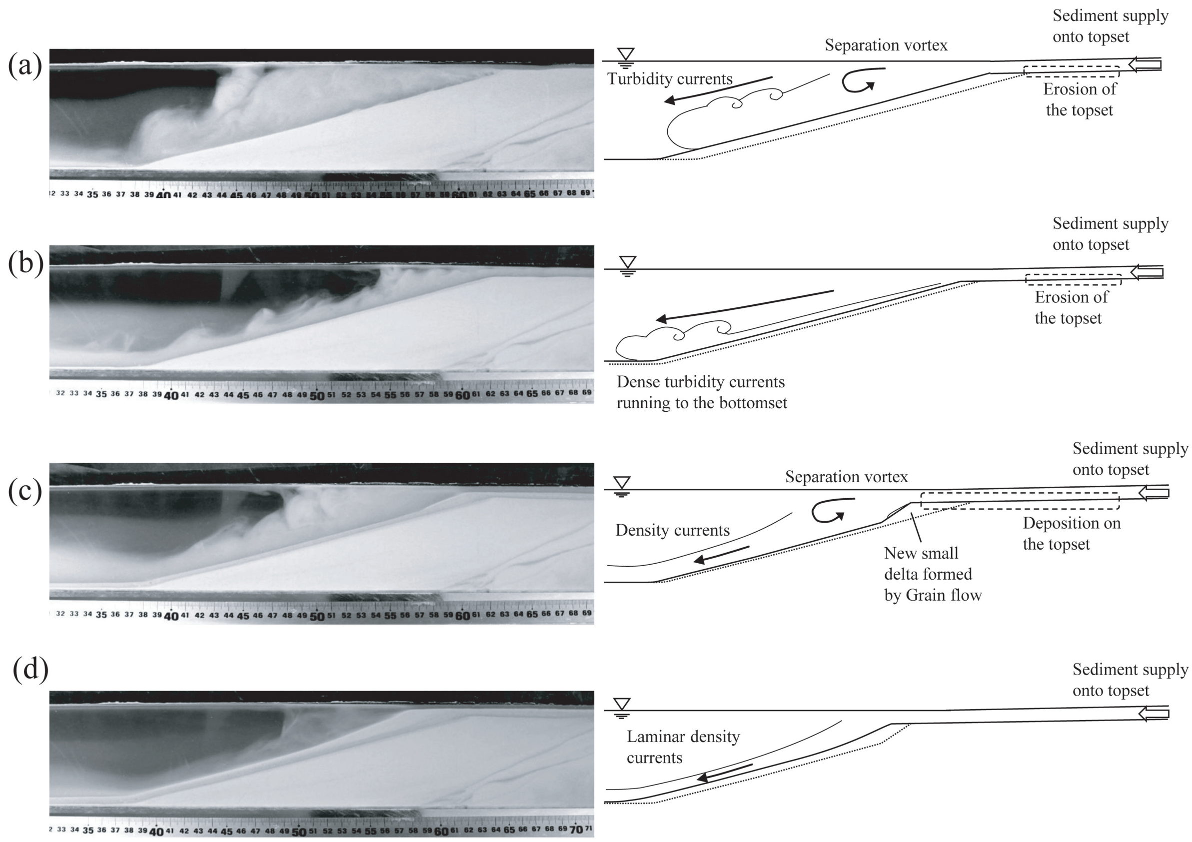

Fig.7 Photos and schematic representations of the delta system at waning stage of Run H-L.
(a), (b), (c), and (d) show 0, 2, 10, and 20 min, respectively, after the start of waning; their instantaneous discharges were at 600, 560, 400, and 200 mL·min^{-1}, respectively. Dotted lines indicate the last stages of delta profiles.

Run L-L. The foreset shape became a gentle slope because of laminar density currents (Fig.7d).

4 Discussion

At an extremely low increase rate (+10 mL·min^{-2}) of water discharge, as expected from the results of constant discharge runs (Fig.2), the deposition rate on the foreset decreased with increasing discharge because the amount of grains transported downstream far from the foreset increased due to flow separation, and the sediment flux conveyed onto the foreset relatively decreased (Fig.3). However, at a high increase rate of discharge (+800 mL·min^{-2}), the deposition rate increased (Fig.6). This contrast occurred because the abrupt increase in water discharge caused the abrupt erosion of the topset, and the increased amount of transported sediment became considerably large to be conveyed as turbidity currents; therefore, the sediment flux onto the foreset increased. It was found that in the case of high increase rate of the discharge the deposition rate increased to a large value even if being compared at the moment of the same water discharge with the constant flow run, because of the high degree of non-equilibrium state.

At waning stage, the deposition rate on the foreset depended on not only decrease rate but also increase rate. At an extremely low decrease rate (−10 mL·min^{-2}) of water discharge after waxing at an extremely low increase rate (+10 mL·min^{-2}), as expected from the results of constant discharge runs (Fig.2), the deposition rate on the foreset increased with decreasing discharge because the amount of grains transported by separated flow downstream far from the foreset decreased because of the depression of flow separation, and the sediment flux conveyed onto the foreset relatively increased (Fig.3). At a high decrease rate, the deposition rate decreased abruptly before it increased regardless of increase rate at waxing stage

(Fig.4b, Fig.6a) because the deposition on the topset occurred due to accommodation caused by erosion of the previous waxing. At a low decrease rate after high rate waxing (+800 mL·min^{-2}) the deposition rate abruptly decreased. Erosion on the topset due to high discharge continued momentarily and caused dense turbidity currents by continuing erosion on the topset. The dense turbidity currents passed through foreset with scarce deposition on the foreset (Fig.6b). Thus, at any decrease rate, the deposition rate recovered to a value similar to that of the constant flow run; however, its midterm path depended on the hydrographic pattern. A comparison of Runs L-H and H-H, which had the same decrease rate of discharge, shows that the increase rate of discharge before waning affects the temporal development of the deposition rate. It can be concluded that the hydrographic pattern, i.e., the history of change in water discharge, influences the deposition rate and the sediment transports.

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