Laboratory Flume Experiments on the Formation of Spanwise Large Wood Accumulations: Part II—Effect on local scour

I. Schalko1,2, C. Lageder2,3, L. Schmocker4, V. Weitbrecht2, and R. M. Boes2

Abstract In this second companion paper, hydraulic model tests were conducted to analyze local scour due to natural spanwise large wood (LW) accumulations. Spanwise accumulations were modeled using a vertical barrier, similar to a LW retention rack in prototype. The flume experiments were conducted according to Froude similitude in a scale of 1:30 for various approach flow conditions (subcritical and supercritical flow) and different uniform bed material (2.7–13.1-mm model dimensions). The findings allow the estimation of local scour depth due to spanwise LW accumulations as a function of unit discharge, sediment diameter, and wood volume. Higher unit discharge, finer bed material, and increasing wood volume lead to an increased scour depth. The scour length can be estimated based on the scour depth and a geometrical scaling factor. The longitudinal shape of the cross-sectional scour depth can be described with a Gaussian normal distribution. Based on the results of both scour depth and length, the design of LW retention structures can be significantly improved. At the same time, the results demonstrate that LW accumulations strongly affect the geomorphic conditions and may consequently create more heterogeneous morphological structures.

1. Introduction

Wood accumulations play an essential role for a river ecosystem, as they create heterogeneous flow conditions and morphological structures (Davidson et al., 2015; Gippel, 1995; Keller & Swanson, 1979). The morphological structures strongly depend on the number of accumulated logs (Wallerstein et al., 2001; Wohl et al., 2016). During floods, large wood (LW) accumulations at retention racks or bridge piers may pose structural hazards due to backwater rise and scour. Estimations of scour due to LW accumulations are therefore essential for flood hazard assessment. The few past studies investigating the influence of LW accumulation on scour focused mainly on local scour at bridge piers or constriction scour, which correspond to partial and not spanwise blockage.

Laursen and Toch (1956) investigated local scour around bridge piers and abutments due to LW accumulations. The accumulation was either formed naturally or preinstalled. For the naturally formed accumulation, a certain LW volume was continuously added to the channel upstream of the pier. The preinstalled accumulation consisted of single logs tied together with cloth stripes to account for different porosities. The results qualitatively showed that the LW accumulation changes the approach flow conditions, leading to deeper and larger scour.

Melville and Dongol (1992) modeled a LW accumulation at a bridge pier as a raft with smooth, impermeable, regular shapes. The raft was mounted on the bridge pier at water-level height. The raft shapes varied between cylindrical, conical, and elliptical; the cylindrical shape resulted in the largest scour. Melville and Dongol (1992) introduced the effective pier diameter $d_{eff}$ (Figure 1), defined as

$$d_{eff} = \frac{0.52h_A d_A + (h_n - 0.52h_A)d_p}{h_n},$$

with $h_A$ is the effective height of LW accumulation (m), $d_A$ is the diameter or width of the LW accumulation (m), $h_n$ is the approach flow depth (m), and $d_p$ is the pier diameter (m). The scour depth $S$ can be estimated...
by replacing $d_p$ with $d_{	ext{eff}}$ in the scour equation by Melville and Sutherland (1988). The local scour reached the maximum magnitude for $h_o/d_p = 4$ and decreased again for higher values of $h_o/d_p$. In summary, local scour was mainly affected by the LW accumulation characteristics, the approach flow depth and velocity, sediment size and grading, as well as pier size, shape, and orientation to the flow.

Lagasse et al. (2010) conducted flume experiments with different accumulation porosities (impermeable versus 25% porosity). According to Lagasse et al. (2010), the concept of the effective pier diameter by Melville and Dongol (1992) tends to overestimate local scour. In addition, it does not consider the effect of the LW accumulation shape. Lagasse et al. (2010) proposed a modification of the effective pier diameter formulae $d_{	ext{eff}}$ to

$$
\text{for } L_A > 1:
\begin{align*}
  d_{\text{eff}} &= K_1 h_A d_A \left( \frac{L_A}{h_o} \right)^{K_2} + \left( h_o - K_1 h_A \right) d_p \\
  \text{for } L_A \leq 1:
  d_{\text{eff}} &= K_1 h_A d_A + \left( h_o - K_1 h_A \right) d_p
\end{align*}
$$

with $L_A$ as the upstream length of the LW accumulation (m). $K_1$ is an empirical, dimensionless accumulation shape factor with $K_1 = 0.79$ for rectangular and $K_1 = 0.21$ for triangular shape (compared to 0.52 in equation (1)). $K_2$ considers the intensity of the downward flow due to the LW accumulation upstream of the pier with $K_2 = -0.79$ for rectangular and $K_2 = -0.17$ for triangular shape. Given a large accumulation, the flow is deflected stronger downward, thereby increasing scour depth. The largest scour was observed for a rectangular LW accumulation with $L_A = h_o$. Compared to the size, shape, and location of the LW accumulation, the porosity had only a minor effect on the resulting local scour (Lagasse et al., 2010). In the proposed equations (2) and (3), the effect of LW volume on $d_{\text{eff}}$ is not included. As the LW accumulation upstream of a bridge pier is not comparable to a spanwise LW accumulation, equations (2) and (3) are not suitable as design equations for the present model tests.

Pagliara and Carnacina (2011) experimentally studied the influence of the transverse cross-sectional geometry of LW accumulations on local scour at bridge piers. The blockage area was identified as the decisive parameter affecting the resulting scour.

The geomorphic and hydraulic impacts of LW elements in sand-bed channels were examined by Wallerstein et al. (2001) with flume experiments. The flow conditions were chosen below the threshold for incipient motion to investigate geomorphic effects solely due to the LW elements. The LW element size was the governing parameter for scour depth and size. Wallerstein (2003) developed an analytical model to describe constriction scour due to small partial LW accumulation. The model was validated using the field and experimental data of the Mississippi River, presented in Wallerstein et al. (2001), and allows to estimate scour rate and depth due to small partial LW accumulation.
Studies on local scour due to spanwise LW accumulations, that is, dam jams (Abbe & Montgomery, 1996; Dixon, 2016), have not been conducted so far. However, the flow through a spanwise LW accumulation is comparable to a horizontal jet. Local scour due to horizontal jets was described by Eggenberger and Müller (1944) as

\[ S + h_2 = W \frac{\Delta h^{0.5}}{d_{90}^{0.6}}, \]  

with \( S \) = scour depth (m), \( h_2 \) = downstream flow depth (m), \( W \) = constant value for jet type \((m^{0.7}/s^{0.6})\) with \( W = 10.35 \) for a submerged jet and \( W = 15.4 \) for a free jet, \( \Delta h \) = difference between upstream and downstream flow depth (i.e., backwater rise in m), \( q \) = unit discharge \((m^2/s)\), and \( d_{90} \) = characteristic grain size diameter \((mm)\).

The studies on morphological effects, in particular local scour, due to LW accumulations focused either on bridge piers or partial LW blockage. The LW accumulation has been simplified as rectangular or triangular shape in the model tests on scour at bridge piers. The interactions between backwater rise and local scour due to LW accumulations have not been studied so far. This second companion paper, therefore, presents the results on local scour due to spanwise LW accumulations for different (1) flow conditions and (2) bed material (mean grain size diameter). This study is conducted in the frame of a doctorate (Schalko, 2018) and part of the interdisciplinary research project WoodFlow—Management of LW in Swiss rivers (Ruiz-Vilanueva et al., 2016).

### 2. Methodology

The experiments were conducted in an 8.0-m-long, 0.4-m-wide, and 0.7-m-deep tiltable flume at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) of ETH Zurich. Detailed descriptions of the experimental setup, model LW and sediment, and test program are summarized in the first companion paper (Schalko et al., 2019) covering the two tests series A and B. The herein presented experiments correspond to test series B (B1–B12).

The formation of a LW accumulation is a random process, which can affect the resulting bed level. To study the variability of our model tests, reproducibility tests (B4 and B5) were conducted, confirming that our test procedure can be repeated with an error of the local scour depth at the rack \( S_r \) of ~15% (Schalko, 2018). The model setup is illustrated in Figure 2.

A given solid LW volume \( V_f \approx 0.023 m^3 \) with a mean log diameter \( d_{Lm} = 10 mm \) was added stepwise to the flow to model a natural accumulation at a rack. The rack was placed 3.4 m downstream of the intake. The rack consisted of seven vertical aluminum bars with a circular cross section of 0.008-m diameter and an
Figure 3. LW accumulation with a movable bed for (a–e) $V/V_c \approx 0.25–5.00$ (B8).
axial spacing of 0.05 m. For the bed material, three different grain sizes with uniform distribution were tested with mean grain size diameters $d_m = 2.7$, 5.4, and 13.1 mm. The geometric standard deviation of the grain size distribution $\sigma_g$ amounted to 1.1–1.2 and the corresponding $d_{90} = 3.1$, 5.9, and 15.4 mm. To investigate local scour solely due to LW accumulations, the initial flow condition (subscript IC) was chosen to represent weak transport, similar to the test setup of Wallerstein et al. (2001). The nondimensional bed shear stress $\theta_{IC}$ was slightly below the nondimensional critical bed shear stress $\theta_{cr}$ for incipient motion. The required values for the initial bed shear stress were visually examined. For a given $d_m$ and $Q$, the bottom slope $J_o$ was continuously increased by tilting the flume until weak transport occurred. The respective $\theta_{IC}$ was determined to be $\theta_{IC} = 0.04$ for $d_m = 2.7$ and 5.4 mm, and $\theta_{IC} = 0.05$ for $d_m = 13.1$ mm. Given this initial condition with $\theta_{IC}$ and a defined $Q$, the different $d_m$ resulted in a range of approach flow Froude numbers $F_o \approx 0.5-1.5$. The specific discharges result to $q = 0.05, 0.075$, and 0.10 m$^2$/s.

The experimental procedure for each test can be described by the following steps:

1. measurement of approach flow depth $h_o$ for a certain approach flow condition without LW accumulation;
2. stepwise addition of packages of 5–10% of $V_s$ with the respective $d_{Lmw}$ and log length $L_L$. The solid LW volume $V_s$ was measured based on the Archimedes’ principle;
3. measurement of resulting flow depth $h$ upstream of the LW accumulation with an ultrasonic distance sensor (UDS) after stabilization of the scour;

Figure 4. Scour with uniform bed material for $V_s/V_c = 2$, $d_m = 2.7$ mm, and (a) $q = 0.05$ m$^2$/s (B8), (b) $q = 0.075$ m$^2$/s (B9), and (c) $q = 0.10$ m$^2$/s (B10). Initial nondimensional bed shear stress was set to $\theta_{IC} = 0.04$ for $d_m = 2.7$ mm.
4. measurement of scour depth at the rack $S_r$ with a point gauge;
5. determination of the loose LW volume $V_l$ based on a videometric analysis of side and top view photographs of the accumulation. With $V_l$ and $V_s$, the bulk factor $a = V_l/V_s$, that is, compactness of accumulation (Schalko et al., 2019) was then derived for each added package of $V_s$;
6. after the addition of 100% of $V_s$, the water was slowly drained, LW manually removed, and the bed topography was scanned in a 0.025-m² grid resolution with a laser distance sensor (LDS; ±1-mm accuracy). The laser distance sensor was placed on a positioning system, which was manually moved in the $x$ (streamwise direction) and $y$ directions (spanwise direction). The origin of the $x$-$z$ coordinate system was located at the rack at initial movable bed level $h_b$ (Figure 2).

3. Results and Discussion
3.1. Effect of Approach Flow Conditions and Bed Material

Figure 3 illustrates the formation of a natural spanwise LW accumulation and the resulting local scour for different ratios between the solid LW volume $V_s$ and the characteristic LW volume $V_c$ (test B8). The characteristic LW volume $V_c$ is the required wood volume that triggers the main backwater rise by blocking large parts directly in front of the rack before a LW carpet starts to form that only slightly leads to further backwater rise (Schalko et al., 2019). For the movable bed experiments, the initial bed shear stress $\delta_{IC}$ was set...
slightly below the threshold value for incipient motion to study local scour solely due to the LW accumulation (section 2). With increasing $V_s$, the rack is blocked and the flow upstream of the accumulation is altered, leading to backwater rise. Due to the smaller flow cross section at the rack, flow velocity and thus the bottom shear stresses increase at the rack, thereby initiating scour formation. Each added LW package leads to a further decrease of the open flow cross section, increasing hydraulic load, and therefore increasing $S_r$ (Figure 3a versus Figure 3e). For $V_s/V_c \leq 1$, not only the main increase in backwater rise occurs but also local scour depth $S_r$. Due to the local scour formation, the LW accumulation can extend along the rack further toward the bottom.

Figure 4 shows $S_r$ for $V_s/V_c = 2$, $d_m = 2.7$ mm, and varying unit discharge $q$ (B8–B10).

![Figure 6](image6.png)

Figure 6. (a) Side view and (b) top view of 2-D scour $S$ for $q = 0.05$ m$^2$/s and $d_m = 2.7$ mm (B8).

![Figure 7](image7.png)

Figure 7. (a) Side view and (b) top view of 2-D scour $S$ for $q = 0.10$ m$^2$/s and $d_m = 2.7$ mm (B10).
transversal cross sectional scour depth (B1, B8, B11), and (c) and (d) longitudinal section of the average Figure 8.

\[ S_r = \text{increasing with increasing } q \] (Figure 4a versus Figure 4c). For \( d_m = 2.7 \text{ mm and } V_s/V_c = 1, S_r = 0.16 \text{ m for } q = 0.05 \text{ m}^2/\text{s}, \) compared to \( S_r = 0.22 \text{ m for } q = 0.075 \text{ m}^2/\text{s}, \) and \( S_r = 0.28 \text{ m for } q = 0.10 \text{ m}^2/\text{s}. \) Similar to increasing \( V_s, \) hydraulic load on the movable bed at the rack likewise increases with increasing \( q, \) leading to larger \( S_r. \)

In Figure 5, \( S_r \) is illustrated for \( V_s/V_c = 1, \) \( q = 0.075 \text{ m}^2/\text{s}, \) and different mean grain size diameters \( d_m = 2.7 \text{ mm, } d_m = 5.4 \text{ mm, and } d_m = 13.1 \text{ mm (B9, B4, B12). Given the same initial condition for sediment transport } (S_{IC} = 0.04 \text{ and 0.05}), S_r \) is decreasing with increasing \( d_m \) (Figure 5a compared to Figure 5c).

For \( V_s/V_c = 1 \) and \( q = 0.075 \text{ m}^2/\text{s}, S_r = 0.22 \text{ m for } d_m = 2.7 \text{ mm compared to } S_r = 0.14 \text{ m for } d_m = 5.4 \text{ mm, and } S_r = 0.07 \text{ m for } d_m = 13.1 \text{ mm. Given equal flow conditions, a larger grain size diameter } d_m \) results in smaller \( \theta \) compared to smaller \( d_m. \) If \( \delta \) is only slightly above \( \delta_{cr} \) for incipient motion, weak sediment transport occurs, resulting in smaller scour depths compared to conditions with \( \delta \gg \delta_{cr}. \) In addition, large \( d_m \) represents a greater erosion resistance, resulting in smaller scour depths.

The scour \( S_r \) topography at test end after the addition of \( V_s = 0.023 \text{ m}^3/\text{s} \) is exemplarily shown in Figures 6 and 7 for tests B8 and B10. Scour volume \( V_{scour} \) for \( d_m = 2.7 \text{ mm increases from } V_{scour} = 29.1 \text{ dm}^3 \text{ for } q = 0.05 \text{ m}^2/\text{s} \) to \( V_{scour} = 69.9 \text{ dm}^3 \text{ for } q = 0.10 \text{ m}^2/\text{s}. \) In comparison, given \( q = 0.05 \text{ m}^2/\text{s}, \) \( V_{scour} = 29.1 \text{ dm}^3 \text{ for } d_m = 2.7 \text{ mm compared to } V_{scour} = 17.1 \text{ dm}^3 \) for \( d_m = 5.4 \text{ mm.} \) The increase in \( V_{scour} \) for increasing \( q \) and decreasing \( d_m \) was observed for all other tests. A symmetric scour along the transverse cross section developed, that is, a 2-D scour. So possible 3-D or wall effects can be neglected for this setup.

In Figure 8a, the scour depth at the rack \( S_r \) normalized with \( d_m \) is plotted as a function of \( V_s/V_c \) for \( d_m = 2.7 \text{ mm and different } q = 0.05-0.10 \text{ m}^2/\text{s} \) (\( F_v < 0.57-0.47). \) For \( V_s/V_c = 1, S_r/d_m = 49 \text{ for } q = 0.05 \text{ m}^2/\text{s}, \) increasing up to \( S_r/d_m = 70 \text{ for } q = 0.10 \text{ m}^2/\text{s}. \) The development of \( S_r/d_m \) is comparable to \( \Delta h/h_o \) as a function of \( V_s/V_c \) (Schalko et al., 2019). For the majority of the tests, \( V_s/V_c > 1 \) generates not only the main increase of \( \Delta h \) but also the main increase of \( S_r. \) For \( V_s/V_c < 1, \) the governing process inducing \( \Delta h \) as well as \( S_r \) is the reduction in open flow cross-section area, whereas for \( V_s/V_c > 1, \) \( \Delta h \) is mainly a function of the friction losses below the LW carpet. As the change in flow cross section is minimal for \( V_s/V_c > 1, S_r \) likewise only increases minimally. The effect of different grain size diameters \( d_m \) on \( S_r/d_m \) is illustrated in Figure 8b. Given \( q = 0.05 \text{ m}^2/\text{s} \) and \( V_s/V_c = 1, S_r/d_m = 49 \text{ for } d_m = 2.7 \text{ mm, } S_r/d_m = 19 \text{ for } d_m = 5.4 \text{ mm, and decreasing to } S_r/d_m = 1.3 \text{ for } d_m = 13.1 \text{ mm.} \) According to Figures 8a and 8b, grain size diameter \( d_m \) imposes a stronger effect on \( S_r \) compared to the approach flow conditions, that is, \( q. \) A longitudinal section of the average cross-sectional scour depth \( S_m \) is shown in Figures 8c and 8d. Compared to the tests with smaller \( d_m, S_m \) varies in the range of only \( \approx 2 \times d_m \text{ for } d_m = 13.1 \text{ mm, indicating the greater resistance of larger } d_m. \)

According to Figures 8c and 8d, the longitudinal shape of \( S_m \) is quite symmetrical. This symmetrical shape is also confirmed for the longitudinal shape of \( S_{max} \) for all tests. The position of the maximum scour depth was slightly shifted upstream of the rack. For the data analysis, it was assumed that \( S_{max} \) is located at the rack with \( x = 0 \text{ cm, that is, } S_{max} \approx S_r. \) The scour (subscript \( S \)) length \( L_S \) was measured for all tests and varies between 0.40 and 2.00 m. \( L_S \) thereby decreases with increasing \( d_m \) and decreasing \( q, \) similar to \( S_{max}. \) The ratio between the relative scour length \( L_S/d_m \) and the relative maximum scour depth \( S_{max}/d_m \) can therefore be described using a geometrical scaling factor as \( (R^2 = 0.97); \)
Figure 9. Relative scour length $L_s/d_{90}$ versus relative maximum scour depth $S_{\text{max}}/d_{90}$ for test series B with $V_s = 0.023$ m$^3$ and equation (5).

The ratio is plotted in Figure 9 for $V_s = 0.023$ m$^3$, test series B, and with equation (5). Assuming a Gaussian normal distribution with $\mu = 0$ ($S_{\text{max}} \approx S_r$ at $x = 0$ cm), $L_s$ can be described by applying the 99.7 rule (Pukelsheim, 1994), so 99.7% of the values lie within 6 standard deviations of the maximum scour depth (subscript $S_{\text{max}}$) $\sigma_{S_{\text{max}}}$. Comparing the 99.7 rule with equation (5), $\sigma_{S_{\text{max}}}$ can be approximated to be equivalent to $S_{\text{max}}$. The probability density function of the normal distribution is now applied to describe the development of the transversally averaged scour depth $S$ in streamwise direction $x$ to

$$S(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{x^2}{2\sigma^2}} = S_{\text{max}} e^{-\frac{x^2}{2\sigma_{S_{\text{max}}}^2}},$$

with the first term, $1/(2\pi\sigma^2)^{1/2}$ describing the amplitude of the normal distribution, which can be substituted with $S_{\text{max}}$. Given $S_{\text{max}} \approx S_r$ at $x = 0$ cm, the position of the mean value $\mu = 0$. Hence, $\mu$ can be neglected. Based on equation (5) and the 99.7 rule, the probability density function can further be simplified by describing $\sigma$ with $S_{\text{max}}$. The longitudinal section of the maximum transversal cross sectional scour depth $S_{\text{max}}$ is exemplarily plotted for three tests (B1, B8, and B11) in Figure 10. The dashed line represents the model scour shape using equation (6). Equation (6) describes the development of $S$ along the $x$ axis compared to the measured data very well and confirms the assumption to estimate the scour shape based on a Gaussian normal distribution.

3.2. Design Equation for Local Scour Depth

To generalize the results, the governing parameters for local scour depth due to spanwise LW accumulation with the initial condition for sediment transport set to $\theta_{\text{IC}} = 0.04$ for $d_m = 2.7$ and 5.4 mm, $\theta_{\text{IC}} = 0.05$ for $d_m = 13.1$ mm and uniform bed material are discussed hereafter. The maximum scour depth $S_{\text{max}}$, that is, scour depth at the rack $S_r$, can be described by the basic parameters in Table 1. The effect of the bed slope $I_o$ is implicitly included in $d_m$ due to the initial condition for sediment transport set to $\theta_{\text{IC}} = 0.04$–0.05 and $q = 0.05$–0.10 m$^3$/s. Similar to the study by Melville and Sutherland (1988) and Melville and Dongol (1992), scour depth at both bridge piers and rack poles is governed by flow intensity (here $q$), sediment grain size diameter, and pier or LW dimensions, respectively.

A dimensional analysis was performed based on the Buckingham theorem $\Pi$ (Buckingham, 1914). According to Heller (2011), a physical problem is described by independent parameters $n$ with reference dimensions $r$ ([M] mass, [L] length, [T] time), resulting in $n - r = \Pi_1, \Pi_2, \ldots, \Pi_{n-r}$ nondimensional parameters. To obtain similitude, the nondimensional parameters have to be identical in model and prototype. The selected $n = 12$ independent parameters include $r = 3$ reference dimensions. Based on a dimensional analysis, $n - r = 9$ nondimensional parameters $\Pi_{1-9}$ need to be defined. The relative unit discharge is described with $\Pi_1 = q/(gd_m^{3/2})$, including the governing parameters in a nondimensional form based on the conducted flume experiments, that is, $q$ and $d_m$. Additional nondimensional parameters are relative sediment density $\Pi_2 = \rho_{\text{sed}}/\rho_w = s$, relative LW volume $\Pi_3 = V_w/V_{\text{fl}}$, geometric standard deviation $s_g$ of the grain size distribution $\Pi_4 = (d_{95}/d_{10})^{0.5}$, relative log length $\Pi_5 = L_{ij}/d_{ij}$, relative LW density $\Pi_6 = \rho_L/\rho_w$, ratio between sediment and LW density $\Pi_7 = \rho_{\text{sed}}/\rho_L$, relative sediment diameter $\Pi_8 = d_m/d_L$, and ratio between log length and sediment diameter $\Pi_9 = L_j/d_m$.

The accumulation shape is a dominant parameter and the accumulation porosity a function of $d_L$, $L_j$, and $\rho_L$. These parameters are implicitly included in $V_w$. However, as the log diameter, log length, and wood density were not varied systematically in this study, $\Pi_{7-9}$ were excluded in the further analysis. Wood density $\rho_L$ may affect the LW accumulation shape, and therefore may alter the scour depth. For increasing $\rho_L$, increasing $\Delta h/h_o$ can be expected and hence, increasing scour depth $S$. However, to test this hypothesis, flume
experiments with varying $\rho_L$ are deemed necessary. All tests were conducted for uniform bed material, that is, $\sigma_g \leq 1.2$, so $\Pi_4$ will not be considered. Scour due to LW accumulation is therefore described by $\Pi_1$–$\Pi_3$. The exponents of the governing parameters were quantified with a nonlinear regression analysis and the dimensionless scour factor $S_A$ is defined as

$$S_A = 0.86 \left( \frac{q}{V_s / (s-1)g d_m^3} \right)^{0.85} \left( \frac{V_s}{V_c} \right)^{0.30}.$$  

According to equation (7), $d_m$ exhibits the largest effect on $S_A$ with an exponent of $-1.28$, followed by $q$ with an exponent of $0.85$, and the relative LW volume with an exponent of $0.30$. The measured maximum scour depth $S_{\text{max}}$ is then normalized using $d_{90}$, similar to equation (4) by Egenberger and Müller (1944). Based on $S_A$, the relative maximum scour depth $S_{\text{max}}/d_{90}$ at the rack can be described by a linear relationship for $F_o = 0.5$–1.5 and $S_A = 0$–120 ($R^2 = 0.97$) with

$$\frac{S_{\text{max}}}{d_{90}} = S_A.$$  

In Figure 11, $S_{\text{max}}/d_{90}$ is plotted as a function of $S_A$ for test series B with equation (8), and ±30% prediction range. All data agree with the proposed design equation and root-mean-square error = 5.2.

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**Table 1**

| Parameters | $d_L$ (m) | $L_L$ (m) | $V_c$ (m$^3$) | $V_s$ (m$^3$) | $q$ (m$^2$/s) | $d_m$ (m) | $d_{84}$ (m) | $d_{16}$ (m) | $\rho_W$ (kg/m$^3$) | $\rho_L$ (kg/m$^3$) | $\rho_{sed}$ (kg/m$^3$) | $g$ (m/s$^2$) |
|------------|-----------|-----------|----------------|----------------|----------------|-----------|-------------|-------------|----------------|----------------|----------------|-----------|

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**Figure 10.** Longitudinal section of the maximum transversal cross sectional scour depth $S_{\text{max}}(x)$ for tests B1, B8, and B11 with $V_s = 0.023$ m$^3$, $d_m = 2.7$ mm, and model scour shape, $S(x)$ (--) (Equation (6)). Initial nondimensional bed shear stress was set to $\theta_{IC} = 0.04$ for $d_m = 2.7$ mm.
In Figure 12a, relative prediction error $\varepsilon$ is plotted versus measured relative scour depth $S_{\text{max}}/d_{90}$, with $\varepsilon$ defined as

$$\varepsilon = \frac{S_A - S_{\text{max}}/d_{90}}{S_{\text{max}}/d_{90}}.$$  

(9)

Parameter $\varepsilon > 0$ corresponds to an overestimation of $S_{\text{max}}/d_{90}$, whereas $\varepsilon < 0$ to an underestimation of $S_{\text{max}}/d_{90}$. The majority of the data points are within a ±30% prediction range. In addition, $\varepsilon$ decreases with increasing $S_{\text{max}}/d_{90}$. Note that for $d_m = 13.1$ mm (grey data points) and $S_{\text{max}}/d_{90} \leq 2$, data points exhibit $6.0 \geq \varepsilon > 2.1$. Therefore, it is further recommended to apply equation (8) for $S_{\text{max}}/d_{90} > 2$.

The residuals $r = \text{observed value} - \text{predicted value}$, that is,

$$r = \frac{S_{\text{max}}/d_{90} - S_A}{S_{\text{max}}/d_{90}},$$  

(10)

are plotted as a function of $S_{\text{max}}/d_{90}$ in Figure 12b. The residual plot indicates no clear pattern and the majority of the data points are clustered in the range of $r \pm 10$, representing a good fit equation (equation (8)) to describe local scour due to spanwise LW accumulation.

An error propagation analysis was conducted for equation (7) and $S_{\text{max}}/d_{90}$. The error propagation law is defined as (Taylor, 1997)

$$e_X = \sqrt{\left(\frac{\partial X}{\partial x_1} e_{x_1}\right)^2 + \left(\frac{\partial X}{\partial x_2} e_{x_2}\right)^2 + \ldots + \left(\frac{\partial X}{\partial x_n} e_{x_n}\right)^2},$$  

(11)

with $e_X$ = error of the target value, $X$ = target value, and $e_{x_n}$ = total error of measured (input) parameter $x_n$. The total errors of the input parameters are summarized in Table 2. Based on the error propagation analysis, the resulting relative errors ($e_{x,r} = e_X/X$) of equation (7) amount to ±6.0%–23.9%. In comparison, the relative errors of $S_{\text{max}}/d_{90}$ result in ±6.0%–16.4%. The sum of relative errors $e_{x,r}$ varies between 12% and 40.3%, resulting in an average prediction range of ±27%, similar to the scatter of the final data evaluation (Figure 11).

Previous studies on the effect of LW on scour were mainly conducted for bridge pier scour. To include the effect of LW, the pier diameter was increased and defined as an effective pier diameter (Lagasse et al., 2010; Melville & Dongol, 1992). In equation (8), however, LW is considered as a separate parameter with the ratio of $V_s/V_c$ and applies to the setup of a spanwise accumulation or retention rack, respectively. The governing parameters of equation (8) (unit discharge and grain size diameter) are comparable to the normalized equation presented by Eggenberger and Müller (1944) describing local scour due to horizontal jets. Given $V_s/V_c \approx 1$ for test B8, the measured scour depth at the rack, that is, maximum scour depth $S_{\text{max}}$. 

![Figure 11. $S_{\text{max}}/d_{90}$ versus $S_A$ for test series B, equation (8), and ±30% prediction range.](image)

![Figure 12. (a) Relative prediction error $\varepsilon$ versus measured relative scour depth $S_{\text{max}}/d_{90}$ for the tested $d_m$ and (b) residuals $r$ versus $S_{\text{max}}/d_{90}$ for the tested $d_m$.](image)
Table 2
Total Errors of Input Parameters for Error Propagation Analysis

| Input parameter                | Total error $e_k$ |
|-------------------------------|-------------------|
| Discharge, $Q$                | ±1%               |
| Channel width, $B$            | ±0.002 m          |
| Relative sediment density, $s$| ±0                |
| Gravitational acceleration, $g$| ±0 m/s²           |
| Mean grain size diameter, $d_m$| ±0.0005 m         |
| Solid large wood volume, $V_s$| ±5%               |
| Characteristic large wood volume, $V_c$| ±10%      |
| Characteristic grain size diameter, $d_{90}$| ±0.0005 m       |
| Maximum scour depth, $S_{max}$ | ±0.001 m         |

3.3. Practical Implications and Limitations

Local scour due to spanwise LW accumulations can be estimated for varying approach flow conditions, bed material, and LW volume using equation (8). It is recommended to apply equation (8) for local scour due to spanwise LW accumulations, for instance fully blocked river cross section or at a retention rack, but not for bridge pier scour due to single pier blockage. The input data for the approach flow conditions and LW volume needed, for example, for equations (7) and (8) can be obtained similar to the procedure for the backwater rise estimation (Schalko et al., 2019). The values for the bed material can be assessed by granulometric analyses (e.g., line-sampling method or gravimetric image analysis using BASEGRAIN (Detert & Weitbrecht, 2013)).

In a first step, the maximum scour depth $S_{max}$ can be compared to the maximum tolerable scour at the cross section. Given scour is possible and tolerable ($\theta_{IC} = 0.04–0.05$), the accumulation type factor $f_A$, for the determination of backwater rise due to LW accumulation $\Delta h$, can then be set to $f_A = 0.30$ (Schalko et al., 2019). This then corresponds to the best-case scenario, where a defined scour is tolerable in order to reduce the expected backwater rise. In contrast to a solid bed, the scour formation reduces backwater effect, thereby contributing to reduced sediment deposition.

The scour length as well as the required length of scour protection can be estimated using equation (5). Based on $L_S$, the longitudinal shape of the cross-sectional scour depth $S$ can be described with a Gaussian normal distribution using equation (6). The scour shape is symmetrical around the position of the maximum scour depth $S_{max}$ at the rack.

The presented flume experiments were conducted with the premise to study local scour solely due to LW accumulation, that is, for weak transport as initial condition for sediment transport ($\theta_{IC} = 0.04–0.05$) similar to Wallerstein et al. (2001), and with uniform bed material. The initial condition for sediment transport as well as the use of uniform bed material were chosen to decrease the experimental effort. At the same time, they represent a simplification of the expected prototype processes, as the dimensionless shear stress highly varies in prototype. Given $\theta_{IC} \ll 0.04$, no sediment transport occurs, thereby reducing the expected scour depth. In contrast, for $\theta_{IC} \gg 0.04$, an increase in scour depth can be assumed. However, the presented model tests were conducted under clear-water conditions. With sediment feeding from upstream, the resulting scour depth will decrease. So the application of equation (8) to determine the local scour depth corresponds to a conservative approach.

The dimensional analysis, error propagation analysis, and analyses of the relative prediction error and the residuals enable to quantify the uncertainties when scaling up the model results. The application of equation (8) is recommended to estimate local scour due to spanwise LW accumulations for $S_{max}/d_{90} > 2$. As the resulting maximum scour depths during floods are mostly higher than $2 \times d_{90}$, equation (8) can be used for the hazard assessment due to LW accumulations.
4. Conclusions and Outlook

Hydraulic model tests were conducted to identify the effect of spanwise LW accumulations on local scour. The experiments were performed with varying approach flow conditions and different uniform bed material. The initial condition for the bed material was defined as weak transport to investigate resulting local scour only due to spanwise LW accumulation. The findings of this present study can be summarized as follows:

1. The scour length $L_S$ can be estimated based on $S_{\text{max}}$ and a geometrical scaling factor using equation (5).
2. The longitudinal shape of the cross-sectional scour depth $S$ can be described with a Gaussian normal distribution using equation (6) and is symmetrical around the position of the maximum scour depth at the rack, that is, $S_{\text{max}} \approx S_r$.
3. The governing parameters to describe the maximum local scour $S_{\text{max}}$ due to LW accumulation are unit discharge $q$, mean grain size diameter $d_{m}$, and relative characteristic LW volume $V_s/V_c$.
4. Local scour increases with increasing $q$ and $V_s/V_c$, and decreasing $d_{m}$. Based on a dimensional analysis, a design equation was deduced to estimate maximum local scour depth $S_{\text{max}}$ due to spanwise LW accumulations (equation (8)). The grain size diameter $d_{m}$ exhibits the largest effect on $S_{\text{max}}$ with an exponent of $-1.28$, followed by $q$ with an exponent of $0.85$, and the relative characteristic LW volume with an exponent of $0.30$. Based on a dimensionless scour accumulation factor $S_A$, the relative maximum scour depth $S_{\text{max}}/d_{90}$ can be described by a linear relationship for $F_o = 0.5$–1.5 and $S_{\text{max}}/d_{90} > 2$ ($R^2 = 0.97$). The application of this equation is recommended for spanwise LW accumulations as well as for the design of LW retention racks.
5. The results of this study contribute to an enhanced process understanding of the formation of LW accumulations and the interactions between flow, LW, and sediment. The design equation for local scour can be easily applied by practitioners and increases the efficient planning of LW retention structures.

To further study the interactions between flow, LW, and sediment, complementary experiments using nonuniform bed material and different initial sediment transport conditions are required. In addition, sediment feeding should be considered to evaluate the sediment continuity at rack structures. Given the same initial conditions for sediment transport, scour depths may decrease with sediment feeding. Furthermore, LW accumulations at vertical racks could then disrupt sediment continuity, so the investigation of different rack structures may be deemed necessary. Compared to natural LW accumulations during floods, the performed model tests are still simplified. A flood hydrograph, log remobilization, log stiffness, and a variation of log densities may influence the LW accumulation formation and therefore affect both backwater rise and local scour.

Notation

The following symbols are used in this paper:

- $a$: Bulk factor
- $B$: Channel width
- $d$: Grain size diameter
- $d_A$: Diameter of large wood accumulation
- $d_{\text{eff}}$: Effective pier diameter
- $d_l$: Characteristic grain size diameter at which $i$-% of the sample is finer
- $d_l$: Log diameter
- $d_{ln}$: Mean log diameter
- $d_{m}$: Mean grain size diameter
- $d_P$: Pier diameter
- $e_X$: Total error of target value $X$
- $e_{X,r}$: Relative total error of target value $X$
- $e_{xn}$: Total error of measured parameter $x_n$
- $F_o$: Approach flow Froude number
- $f_A$: Accumulation type factor
- $g$: Gravitational acceleration
- $h$: Flow depth with large wood accumulation

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- $F_o$: Approach flow Froude number
- $f_A$: Accumulation type factor
- $g$: Gravitational acceleration
- $h$: Flow depth with large wood accumulation
\( h_A \) Large wood accumulation height
\( h_b \) Movable bed height
\( h_o \) Approach flow depth
\( h_2 \) Downstream flow depth
\( J_o \) Bottom slope
\( K_{1-2} \) Dimensionless accumulation shape factor
\( L_A \) Large wood accumulation length
\( L_L \) Log length
\( L_S \) Scour length
\( Q \) Discharge
\( q \) Unit discharge
\( R^2 \) Coefficient of determination
\( r \) Residuals
\( S \) Scour depth
\( S_m \) Average cross sectional scour depth
\( S_{max} \) Maximum scour depth
\( S_r \) Scour depth at the rack
\( S_{r, pred} \) Predicted scour depth at the rack
\( s \) Relative sediment density
\( V_c \) Characteristic large wood volume
\( V_l \) Loose large wood volume
\( V_s \) Solid large wood volume
\( v_o \) Approach flow velocity
\( W \) Constant for jet type
\( X \) Target value
\( \bar{x} \) Mean or expected value
\( \Delta h \) Backwater rise
\( \varepsilon \) Relative prediction error
\( \lambda \) Scale factor
\( \mu \) Mean value
\( \rho_L \) Wood density
\( \rho_{sed} \) Sediment density
\( \rho_W \) Water density
\( \sigma_g \) Geometric standard deviation of the grain size distribution
\( \sigma_{Sm} \) Standard deviation of average cross sectional scour depth
\( \theta_{IC} \) Nondimensional bed shear stress of initial condition
\( \theta_{cr} \) Nondimensional critical bed shear stress

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