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COMMENT

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Key Points:

- Follett et al. (2020a, https://doi.org/10.1029/2020gl089346) predicted backwater rise by log jams using river slope and roughness. We show the Froude number can be used instead
- By using the Froude number, the link to the local river conditions becomes stronger, improving formula applicability in engineering practice
- The resulting formula is shown to be similar to earlier empirical work. But differences in jam porosity effects call for further study

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Comment on "Momentum and Energy Predict the Backwater Rise Generated by a Large Wood Jam" by Follett, E., Schalko, I. and Nepf, H.

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Abstract Follett et al. (2020a, https://doi.org/10.1029/2020gl089346) developed an analytical model to predict backwater rise by log jams, using the size and packing density of logs and the jam length, as well as river slope and bed roughness. We show that the model formulas can be rewritten using the Froude number instead of river slope and roughness, thus improving their applicability in engineering practice. The equation terms and results of Follett et al. (2020a, https://doi.org/10.1029/2020gl089346) are found to be similar to those of the empirically derived formula by Schalko et al. (2018, https://doi.org/10.1061/(asce)hy.1943-7900.0001501). However, some differences are identified, calling for further study. Most notably, these distinctions pertain to the effect of accumulation porosity, with additional minor differences in the exponent of the Froude number. Lastly, model implications for some broader applications are explored, showing a methodology to calculate the representative log size for log mixtures, and the expected effect of log orientation on backwater rise.

Plain Language Summary Accumulations of wood in rivers (log jams) can block the flow and thereby cause water level rise. Follett et al. (2020a, https://doi.org/10.1029/2020gl089346) developed a theoretical model to predict how this water level rise depends on log jam properties and local river conditions. For the local river conditions, they used the river slope and bottom roughness. In this comment, we show that the Froude number can be used instead, with exactly the same result. The Froude number is a dimensionless number that depends directly on the local river conditions, making the adapted formula easier to apply in practice. The resulting formula shows good agreement with an earlier one based on experimental work by Schalko et al. (2018, https://doi.org/10.1061/(asce)hy.1943-7900.0001501). Still, some differences were found that raise questions. Most notably, the formulas differ for the effect of accumulation porosity. This becomes especially clear when logs are packed closely together. Next, model implications for slightly different settings than those studied by Follett et al. (2020a, https://doi.org/10.1029/2020gl089346) were explored. This showed how to determine the average log size for a mixture of logs with different sizes, and how the expected water level rise changes with log orientation.

1. Introduction

Follett et al. (2020a) demonstrated that a box-shaped log jam can be modeled as a porous obstruction, generating momentum loss proportional to the number, size, and packing density of the logs and the jam length. These factors were combined to predict backwater rise based on unit discharge and a dimensionless structural jam parameter C_A. They validated their analytical model with experimental data, primarily from Schalko et al. (2018) and additionally from their own experiments (Follett et al., 2020a), and found good agreement. We commend their important contribution, and would like to draw attention to the novel equations for backwater rise by large wood that they developed as part of their work, as these were written in their supplementary material and might have been overlooked by some readers. More specifically, in this comment, we first aim to rewrite their formulations, using Froude numbers instead of a friction factor and river slope. Second, we will discuss the resulting equations, pointing out similarities and differences with the equation that Schalko et al. (2018) found through dimensional analysis and empirical fitting. Third, we will explore some implications of these formulas for broader applications, with jam configurations other than uniformly sized logs with a flow-perpendicular orientation.

2. Calculation of Backwater Rise

Follett et al. (2020a) distinguished between two cases: larger accumulations with falling water behind the jam ($H_3 > H_4$) that generate more backwater rise, and smaller accumulations without falling water ($H_3 = H_4$, see

Figure 1 in Follett et al. (2020a) for the definition of water depths H_1 to H_4). In both cases, the water depth H_2 directly upstream of the accumulation was assumed equal to the undisturbed upstream water depth H_1. The goal is to derive equations that predict the backwater rise (H_1/H_4) based on undisturbed flow conditions. In their equations, Follett et al. (2020b) used the dimensionless structural jam parameter C_A, river slope S and a bed friction factor C_f that depends on the relative submergence of sediment grains (Equations 1a and 1b, for details see supplementary material Follett et al., 2020b). In this comment, we would like to show that this can alternatively be expressed using the Froude number (Equations 2a and 2b, derived below, with $Fr_4 = u_4/\sqrt{gH_4}$).

Essentially, the novelty of this approach lies in the description of the downstream unit discharge q_4. For Equation 1, Follett et al. (2020b) assumed equilibrium between the bottom drag force and the gravitational force $\left(\rho C_f u_4^2 = \rho g H_4 S,\ \text{giving}\ q^2 = u_4^2 H_4^2 = g H_4^3 S/C_f\right)$, plus an additional model to predict C_f. The elegance of our approach is that it is based only on the Froude number, and therefore on the intrinsic flow characteristics ($q^2 = Fr_4^2 g H_4^3$, derived in Equation 4), without requiring further assumptions and models. Hereby, it results in a stronger link to the local river conditions and allows for easier practical application of these formulas.

$$\text{if} \quad q > \sqrt{2gH_4^3/C_A} \quad \text{then} \quad \frac{H_1}{H_4} = \sqrt{3}\sqrt[3]{\frac{C_A S}{2C_{f4}}}, \quad H_3 > H_4 \text{ (falling water)} \tag{1a}$$

$$\text{if} \quad q < \sqrt{2gH_4^3/C_A} \quad \text{then} \quad \frac{H_1}{H_4} = \sqrt{1 + \frac{C_A S}{C_{f4}}}, \quad H_3 = H_4 \text{ (no falling water)} \tag{1b}$$

$$\text{if} \quad Fr_4^2 C_A > 2 \quad \text{then} \quad \frac{H_1}{H_4} = \sqrt{3}\sqrt[3]{\frac{C_A Fr_4^2}{2}}, \quad H_3 > H_4, \quad \frac{H_1}{H_4} > \sqrt{3} \tag{2a}$$

$$\text{if} \quad Fr_4^2 C_A < 2 \quad \text{then} \quad \frac{H_1}{H_4} = \sqrt{1 + C_A Fr_4^2}, \quad H_3 = H_4, \quad \frac{H_1}{H_4} < \sqrt{3} \tag{2b}$$

2.1. Case A: With Falling Water

Given that $H_1 = H_2$, the desired backwater rise can be calculated using Equation 3. Based on momentum and drag calculations, Follett et al. (2020a) found, for the case with falling water, that $H_2/H_3 = \sqrt{3}$ (their Equation 6) and that $H_3 = \sqrt[3]{\frac{C_A q^2}{2g}}$ (their Equation 7). The unit discharge q^2 can then be rewritten using the Froude number (Fr_4) and H_4 (Equation 4), resulting in Equation 5. Substituting this result and $H_2/H_3 = \sqrt{3}$ into Equation 3 finally results in Equation 2a.

$$\frac{H_1}{H_4} = \frac{H_2}{H_4} = \frac{H_2}{H_3} \cdot \frac{H_3}{H_4} \tag{3}$$

$$Fr_4 = \frac{u_4}{\sqrt{gH_4}} \Rightarrow q = u_4 H_4 = Fr_4 \sqrt{g} H_4^{1.5} \Rightarrow q^2 = Fr_4^2 g H_4^3 \tag{4}$$

$$H_3 = \sqrt[3]{\frac{C_A Fr_4^2 g H_4^3}{2g}} = H_4 \sqrt[3]{\frac{C_A Fr_4^2}{2}} \tag{5}$$

2.2. Case B: Without Falling Water

Follett et al. (2020a) found that $H_2^2 = H_3^2 + \frac{C_A q^2}{g H_3}$ (their Equation 3). For the case without falling water behind a jam, $H_1 = H_2$ and $H_3 = H_4$, resulting in Equation 6. After substituting q^2 from Equation 4, Equation 2b is obtained.

$$H_1^2 = H_4^2 + \frac{C_A q^2}{g H_4} \Rightarrow H_1 = \sqrt{H_4^2 + \frac{C_A q^2}{g H_4}} \Rightarrow \frac{H_1}{H_4} = \sqrt{1 + \frac{C_A q^2}{g H_4^3}} \tag{6}$$

3. Discussion

The previous equations use the dimensionless structural jam parameter C_A, based on accumulation length L_A, drag coefficient C_D, and spatially averaged frontal jam area per jam volume a (Note on L_A: the subscript A for accumulation is added here after Schalko et al. (2018), to prevent confusion with log length L_L.) For box-shaped accumulations of identically (or similar) sized cylindrical logs that are uniformly spread and oriented perpendicular to the flow, C_A can be described by Equation 7, using $a = 4\phi/(\pi d_L)$, solid fraction ϕ, log diameter d_L and $C_D = 1$ (Follett et al., 2020a).

$$C_A = \frac{L_A C_D a}{(1-\phi)^3} = \frac{4}{\pi}\frac{L_A \phi}{d_L (1-\phi)^3} \tag{7}$$

Expanding C_A in the backwater rise equations (Equation 2) allows for easier comparison with formulas from previous literature. This is done in Equations 8a and 8b, with purely a rewriting of terms, so results remain identical to those that Follett et al. (2020a) validated against the flume experiments of box-shaped accumulations of large wood by Schalko et al. (2018). This raises the question of how the equation terms and performance compare to those of Equation 9, developed by Schalko et al. (2018) based on the same experiments.

$$\frac{H_1}{H_4} = \sqrt{3}\sqrt[3]{\frac{C_A Fr_4^2}{2}} = 1.49 \cdot Fr_4^{2/3}\left(\frac{L_A}{d_L}\right)^{1/3}\frac{\phi^{1/3}}{1-\phi}, \qquad Fr_4^2 C_A > 2 \tag{8a}$$

$$\frac{H_1}{H_4} = \sqrt{1 + C_A Fr_4^2} = \sqrt{1 + 1.27 Fr_4^2\left(\frac{L_A}{d_L}\right)\frac{\phi}{(1-\phi)^3}}, \qquad Fr_4^2 C_A < 2 \tag{8b}$$

$$\frac{H_1}{H_4} = 1 + 5.4 \cdot Fr_4\left(\frac{L_A}{d_L}\right)^{1/3}\phi^{4/3} \tag{9}$$

These equations contain the same variables and show similar behavior, despite Equations 8a and 8b being based on momentum loss theory and Equation 9 on a dimensional analysis and empirical fitting. Focusing on Equation 8a, as larger jams are more interesting, term $(L_A/d_L)^{1/3}$ appears identically in Equations 8a and 9, and Fr_4 with similar exponents ($Fr_4^{2/3}$ vs. Fr_4). However, for solid fraction ϕ, Equation 8a is proportional to $\phi^{1/3}/(1-\phi)$, versus $\phi^{4/3}$ in Equation 9. Also, note that Equation 9 starts with "1 +," because the relative backwater rise $\Delta H/H_4$ originally predicted by Schalko's formula is converted to absolute terms, that is, H_1/H_4.

To further investigate how the behavior of Equations 8 and 9 compare, Figure 1 plots the predicted results for a hypothetical scenario with $L_A = 3$ m, $d_L = 0.5$ m, and $Fr_4 = 0.6$ (Figures 1a and 1c) or $\phi = 0.35$ (Figure 1d). First, Figure 1a shows how for a given jam length and log diameter, the jam parameter C_A increases with solid fraction ϕ. Consequently (Figure 1c), the backwater rise predicted by Equation 8 increases. Alternatively, the Froude number instead of solid fraction can be varied (Figure 1d), also leading to an increasing water level. In both cases, the transition between the domain without falling water behind the jam (Equation 8b) and with falling water (Equation 8a) occurs by definition at a water depth of $H_1/H_4 = \sqrt{3}$. At this point, Equations 8a and 8b are equal in value and derivative, resulting in a smooth transition. According to Equation 2, $C_A Fr_4^2$ must be 2 at the transition point. Hence, the critical value for the Froude number at which this transition occurs, is $Fr_{4,C} = \sqrt{2/C_A}$. Figure 1b plots the critical Froude number for the considered hypothetical jam scenario ($L_A = 3$ m, $d_L = 0.5$), and shows the transition coordinates of Figures 1c and 1d: $\phi = 0.28$ for $Fr_4 = 0.6$, and $Fr_4 = 0.45$ for $\phi = 0.35$.

Comparing the waterlevel predicted by Equations 8 and 9 in Figure 1c, both formulas agree reasonably well. However, Equation 9 clearly exhibits a more linear shape with respect to ϕ, due to the different presence of ϕ in Equations 8 and 9. For extremely dense accumulations ($\phi > 0.6$), they increasingly diverge. Most natural log jams have solid fractions between 0.2 and 0.5 (Lange & Bezzola, 2006), so these values are quite extreme, and, in fairness, beyond the range of experimental data both formulas are based on. Simultaneously, uncommonly dense accumulations are interesting from a practical point of view, since they induce the highest backwater rise and hence the largest flooding danger. As such, this difference calls for future research on extremely dense logjams, especially the dense heterogeneous mixtures commonly observed during floods (e.g., Korswagen et al., 2022). Next,

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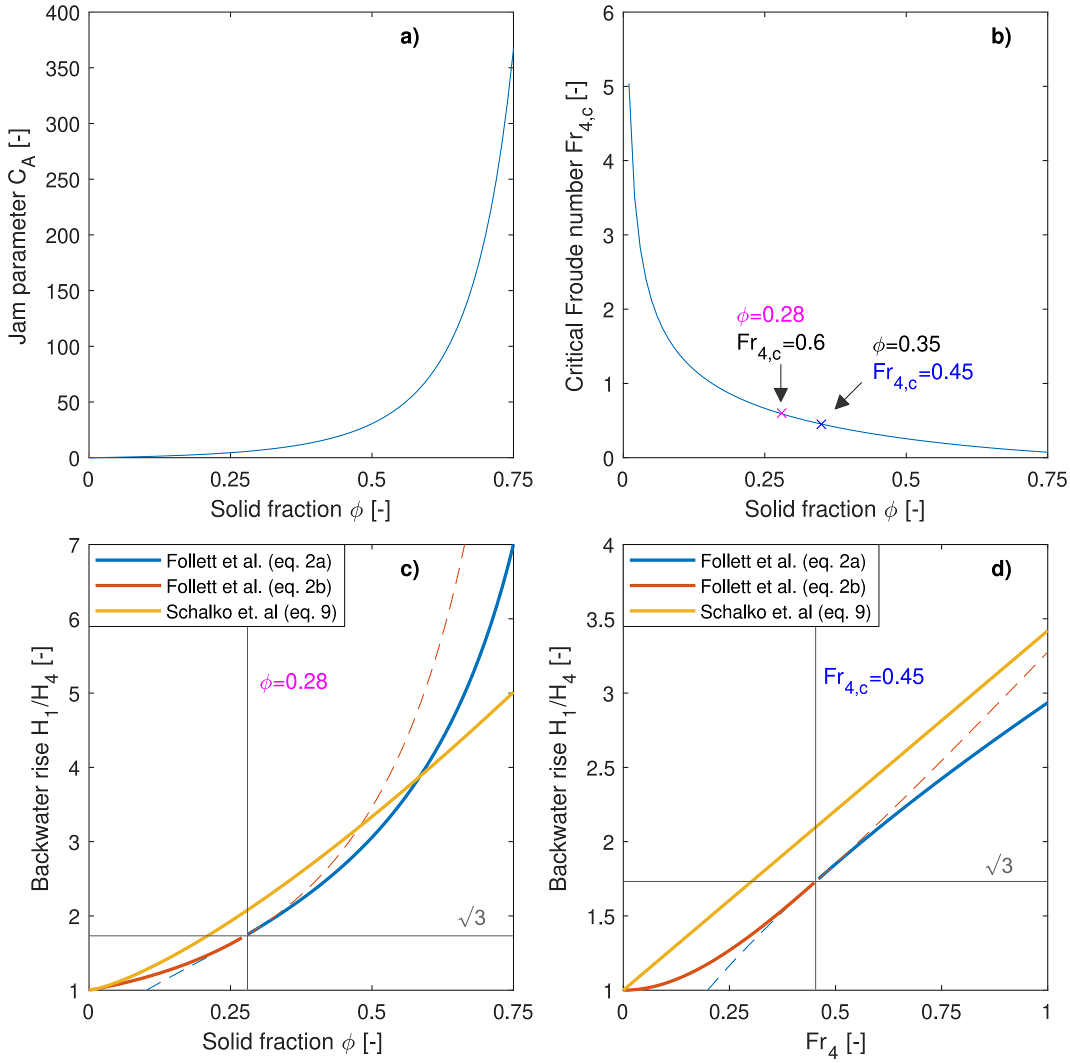

Figure 1. Comparison of the behavior of Equations 8 and 9, for a hypothetical case with $L_A = 3$ m, $d_L = 0.5$ m, with $Fr_4 = 0.6$ (subplot a, c) and $\phi = 0.35$ (subplot d). The horizontal lines at $H_1/H_4 = \sqrt{3}$ indicate the transition from Equations 2a to 2b. Dashed lines in panels (c and d) indicate results of Equations 2a and 2b outside their applicability range. Note: ϕ ranges by definition between 0 and 1, but in practice values between 0.2 and 0.5 are more common.

looking at the effect of the Froude number while jam geometry is kept fixed (Figure 1d), both formulas again agree reasonably well. However, Equation 9 shows a linear line through (0,1), while the compound nature of Equation 8 gives a slightly S-shaped curve: fairly flat at $Fr_4 = 0$, with increasing steepness for low Froude numbers (i.e., $Fr_4 < Fr_{4,C}$, Equation 8a) and slowly decreasing steepness for high froude numbers (i.e., $Fr_4 > Fr_{4,C}$, Equation 8b). Note that for practical applications the result at very low Froude numbers is less relevant, as these flow conditions are unlikely to create the (uniform) log jams considered here. While we appreciate the advantage of the theoretical foundation underlying Follett's formula, the identified differences call for comparison of both formulas' predictions to experimental observations, especially with respect to the predicted existence of two regimes and the linearity of the effect of the Froude number.

The equal presence of log diameter and accumulation length in both equations not only provides extra confidence in these formulas, but also additional insight. Log diameters are used by Follett et al. (2020a) to calculate a, the spatially averaged frontal area of logs per accumulation volume, which is needed for the integration of the total drag force. This calculation can be extended for log mixtures instead of identical logs. Assuming that the drag from an individual log only depends on log size through its frontal area and volume (i.e., that approach flow velocities within the jam are independent of log size), Equation 10 can be applied. For Schalko's equation, which used a mean log diameter (d_{Lm}) for mixtures, it then makes sense to use the same weighted average, that is, $d_{Lm} = \sum\left(d_L^2 L_L\right) / \sum(d_L L_L)$

$$a = \frac{A_{fr,logs}}{V_{jam}} = \frac{A_{fr,logs}}{V_{logs}/\phi} = \underbrace{\phi \frac{\sum d_L L_L}{\sum 0.25\pi {d_L}^2 L_L} = \frac{4\phi}{\pi} \frac{\sum d_L L_L}{\sum {d_L}^2 L_L}}_{\text{if logs perpendicular to flow}} \quad \underbrace{= \frac{4\phi}{\pi d_L}}_{\text{if logs also identical}} \tag{10}$$

The flow resistance of other jam configurations can be calculated following the same method. For instance: for uniform cylindrical logs oriented parallel to the flow, $a = \phi \frac{0.25\pi d_L^2}{0.25\pi d_L^2 L_L} = \frac{\phi}{L_L}$. Accordingly, following Equations 7 and 8a, identical logs oriented parallel to the flow are expected to create a factor $[4L_L/(\pi d_L)]^{1/3}$ less backwater rise than flow-perpendicular logs (ignoring a small change in drag coefficient), for example, a factor 2.9 for $L_L/d_L = 20$. In a similar manner, this method could be used to study effects of other debris shapes. Hereto, experimental validation would be required, as follow-up of the valuable research of Schalko et al. (2018) and Follett et al. (2020a).

Data Availability Statement

Data were not used, nor created for this research.

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