Responses to reviewers of "Open check dams and large wood: head losses and release conditions", First review

Edition style of responses

The comments of Reviewer #1 are written after "Reviewer Comment"

The responses by the authors follow in normal style.

Comment by the Editor

Reviewer Comment: 1. Editor Decision: Reconsider after major revisions (further review by editor and referees) (30 Jul 2020) by Sven Fuchs
Comments to the Author:
Dear colleagues,

first of all, I would like to thank you for submitting your interesting piece of work to NHESS. Meanwhile I received two independent referee opinions on your manuscript, and, as you may have noticed, they come to different decisions.
I particularly went through your responses provided during the open discussion phase. As I can see from your comments, revisions are planned accordingly. I kindly invite you to undertake necessary adjustments, and to provide me with a step-by-step answer together with the new (track-changed) version of your manuscript.
I wish you good success wit your work, and I am looking forward to receiving your revised version. The new version will be sent out to the referees again.
Kind regards,

Sven Fuchs (Editor NHESS)

On behalf of all co-authors, we would like to thank both the reviewers and the editor for the time they took helping us with their comments.

The paper has been thoroughly revised and a native speaker checked the English. Justification and limitation related to the experimental set up, following questions by both reviewers on different subjects, were added (manuscript with tracked changes: L153-166, 209-213, 236-241). Another point that embarrassed Reviewer #1 was that we do not provide a single value of possible head loss related to large wood but prefer to provide ranges of possible effects. This is because random variations in the process are significant and we think more appropriate to work with best- and worse-scenarios than with mean estimates. We know from his work that the Editor is well aware of this challenge. We hope that the response we provided to Reviewer #1 along with the adaptation of the text (L531-538 on paper with tracked changes) will be considered suitable. Finally, a Notation section was added and a couple of references we discovered recently were added to Table 2 and in the Introduction.

We hope the Editor, the Reviewers and the community will find our paper interesting and appropriate for publication in NHESS.

Looking forward to read your feedback.

All the best

On behalf of all co-authors,
Guillaume PITON

Comments by Reviwer #1

Reviewer Comment: 2. ***General comments***

Reviewer Comment: 3. The authors present an interesting paper on the effect of large wood (LW) at various open check dams on hydraulic conditions. Based on an extensive data set, the authors describe resulting backwater rise due to LW blockage at check dams and analyze the process of LW overtopping the dam structure. From a flood hazard perspective, it is very important to determine when LW may pass the retention structure as this can increase flooding downstream. The authors introduce dimensionless parameters to 1) describe the physical process of LW overtopping and 2) inform engineers what relative overtopping flow depth results in LW overtopping. The paper fits very well to the scope of the Journal and provides new insights regarding the interaction between LW and hydraulic infrastructures.

The authors thank very much Reviewer #1 for his/her constructive comments and time spent in helping us to improve our work.

Reviewer Comment: 4. My general comments concern the description of the physical experiments, analysis of effect of LW characteristics, workflow to apply the "non-dimensional parameter describing the formation of a LW carpet", and the form (language) of the paper: The description of the experimental procedure should be improved. It is not clear to me how the authors added LW (L180 ff).

We will clarify how LW was added to the flume adding the sentences hereafter to the section describing the experimental protocol: "Logs were introduced manually at the upstream end of the flume, by groups of 5-15 logs, in an uncongested or semi-congested mode (*sensu* Ruiz-Villanueva et al. 2019). […]. During each discharge step, we continuously checked that at least a couple of logs were recirculating and we introduced more when it was not the case."

We hope it is clearer.

Reviewer Comment: 5. A table of the test program should be added.

Good point. A table with all tests and data will be added to the supplemental data.

Reviewer Comment: 6. In addition, the authors refer to Piton et al. 2019b regarding the experiments. Please clarify the difference between the reference and this present study.

The report Piton et al. 2019b is the scientific report describing this experimental campaign. It was delivered to the French Ministry of Environement, that funded this study. The report is written in French and has not been peer-reviewed. In essence, it is an extended pre-print of the present paper. Since several pictures and details of the experimental apparatus are provided in this report, we though fair and useful to mention its existence.

Reviewer Comment: 7. 2. The proposed computational steps to determine the effect of LW on stage-discharge relationship (beta1 and beta2) are easy to follow, but the resulting values exhibit large variations. The authors do propose that engineers calculate upper and lower boundaries, but recommendations on how to select a final value or how to proceed are missing.

This is a very good comment. A key lesson we learnt from this work is that LW jamming open check dam always trigger head losses, however this head losses varies in magnitude. Although previous work demonstrate that some parameters (e.g., presence of fine material) typically increase head losses, we observed wide variability in the beta coefficient values. We think that designers should acknowledge this variability and consider it.

In our opinion and experience, rather than trying to compute a mean value of the head losses, we recommend to use upper and lower bounds as “pessimistic” and “optimistic” scenarios. The challenge is to define which bound is pessimistic (or optimistic); actually, it is a matter of perspective. For instance, if one is intesrested in the design of the dam wings, the optimistic scenario is obviously the one with lower head losses and flow levels and the pessimistic scenario is the one with high head losses. On the contrary, when computing the sediment trapping capacity, the higher the head loss, the higher the deposition. Thus, the pessimistic scenario is the one with low water level and thus head losses. In essence, we recommend designers to consider two extremal scenarios rather than a mean behaviour, and to use each scenario whenever it is the conservative option as an assumption for further design steps.

We agree that this point was not described in the paper and we will add it in the discussion.

Reviewer Comment: 8. 3. The experiments were conducted for various LW dimensions. However, the effect of LW mixture or presence of organic fine material is not discussed. Due to the presence of organic fine material, the resulting backwater rise increases, as depicted in Figures 6-9. The paper would benefit from a short discussion on the effect of FM on backwater rise, as it also enables the comparison to previous studies with branches and leaves.

Indeed, presence of fine material was consistently demonstrated to be a key factor increasing head losses in previous studies. However, we did not observed consistently higher values of Beta coefficient in presence of pine needle. It was yet visible in Figure 12 but was not commented. We will discuss this point in the revised version of the paper.

Reviewer Comment: 9. 4. The authors introduce a dimensionless parameter describing when a LW carpet forms or when a more compact LW accumulation can be expected. I agree with the authors that the ratio of buoyancy to drag force has not been presented in that form yet. However, Schalko et al. (2019, Water Resources Research) state that “The initiation of a LW carpet formation corresponds to the state, where the buoyancy force is higher than the downward drag force.” The reference is included in this paper but the concept of the “characteristic LW volume generating the primary backwater rise prior to the formation of a LW carpet” is not discussed and no reference added when the ratio of the forces are presented. I recommend adding this reference, as it provides a great opportunity to compare the present analysis with other approaches.

Thank you for this suggestion. The many recent works by the ETH team clearly influenced us a lot. We fully agree that this concept of balance between drag force and buoyancy is both explicitly and implicitly described in the work by Schalko et al. and our contribution was merely to propose a dimensionless number to describe the concept. We will revised the section to give proper credit where credit is due.

Reviewer Comment: 10. In addition, it should be added that the application of this concept (to identify how LW accumulates), required first to determine the resulting backwater rise and then insert this value to U in F_D; it would be interesting to discuss the limitations, as beta1 and beta2 exhibit large variations.

Good point. This is precisely why we address both the computation of head losses and the release conditions criteria (h* and Pi/F_D, both functions of h) in the same paper. The interconnection was stated in the discussion but we will try to make it clear earlier in the paper.

Reviewer Comment: 11. 5. The authors include a section regarding comparison to previous work with an interesting table. However, in the text the authors compare their results only to Schmocker and Hager. I recommend to either include more quantitative comparison or shorten the section.

Thank you for the suggestion. We will add comparison with other papers in the text and not limit them to the table.

Reviewer Comment: 12. 6. The paper is well-structured, and the majority of the figures are very informative. However, the paper is very difficult to read. I strongly recommend that the revised paper is proofread by a native speaker. Please also check consistency of terminology (see technical comments).

The revised paper version will be checked by a native speaker. Sorry for that.

Reviewer Comment: 13. Based on these general comments, I propose the paper needs ***major revision in content and form****. I added more detailed comments below.*

Thanks again for the very relevant comments and helpful suggestions.

Reviewer Comment: 14. ***Specific comments***

Reviewer Comment: 15. ***Keywords***

Reviewer Comment: 16. Recommendation: add driftwood (or replace woody debris using driftwood)

Ok, done.

Reviewer Comment: 17. Hyper-congested LW transport is defined as LW transport at the very front of a flood wave, where the amount of transported LW significantly exceeds the amount of water. As the type of transport is not discussed in this paper, I would recommend writing congested LW transport and also add this term in the text.

Well, hypercongested flow regime with "wetted front" are also described in Ruiz Villanueva et al. 2019 but we agree that the LW congestion regimes were not described in the paper and we will add them in the revised version.

*Reviewer Comment: 18. **Abstract***
Reviewer Comment: 19. The authors use the term “energy dissipation” in the abstract and also in the entire ms. I would recommend replacing this term with hydraulic losses, as energy dissipation in this context is very confusing.

Thank you for the suggestion. “Energy” will be replaced by “energy head” in the revised paper and “energy dissipation” by energy “energy head loss”.

*Reviewer Comment: 20. **Introduction***

Reviewer Comment: 21. L82/84: The experiments were conducted without sediment. I recommend to either remove the sentences regarding sediment transport or add information on how to derive effect on sediment transport and elaborate more in detail how flow above the structure affects sediment transport.

The following mention will be added in the revised paper after the mention of sediment. “(see Piton and Recking, 2016a, on this question).”

*Reviewer Comment: 22. **Computing open check dam discharge capacity***

Reviewer Comment: 23. L95: The terminology of flow energy in m is not correct; please use “energy head” (energy is confusing with [m] as units); in addition vertical height above datum is missing.

Agree, as mentioned before, we will correct this point. The level datum is located at the opening bottom, this will be mentioned in the revised version.

Reviewer Comment: 24. L98: The authors state a range of flow Froude number F between 0.01 and 0.3. F = 0.01 this is very small; is this a common value at check dams - in particular when the authors stated in L80 that the flow Froude number is expected to be larger at check-dams compared to reservoir dams. Please discuss.

Froude number with LW varies between 0.01 and 0.3. It was specifically low for the closed dam, which is quite similar to a dam reservoir structure. The bigger the opening, the higher the Froude number as shown in Figure 1.

FIGURE 1 HERE

Figure 1: Froude number with and without LW for each dam type

We know from other experiments with the same flume setting that the Froude number without structure would be close from 0.7 but the presence of open check dams tend to create a significant backwater and decrease of the Froude Number directly upstream.

In the revised version of the paper, the following mention will be added in the Material and methods section: “The mean value ± standard deviation of the Froude number was 0.04 ± 0.01, 0.06 ± 0.02, 0.1 ± 0.02 and 0.24 ± 0.08 for the closed, slit, slot and Sabo dam, respectively (see section 3.2 for dams’ features).”

*Reviewer Comment: 25. **Materials and Methods***

Reviewer Comment: 26. Add more details on the experimental setup. Why did you choose the respective slope,

We will add the following sentence to the section: “This slope is relatively low but is commonly observed in bedload retention basin (Piton et al. 2015, p. 22). This slope is the order of magnitude of channel slopes in alluvial fan distal reaches, i.e., the slope used for the design of guiding channels that are increasingly used in open check dams (Schwindt et al., 2018, Piton et al., 2019c). In addition, since the open check dams triggered high backwater rise and subcritical flow regime (with and without wood), the bottom flume slope is of secondary importance: flow conditions are controlled by the open check dam."

Reviewer Comment: 27. what is the accuracy of the measurement devices?

This information will be added.

Reviewer Comment: 28. Regarding flow depth measurement: what if LW accumulated 20 cm upstream of the dam - how did you account for that?

Good remark. The paper focuses on the design of the barrier itself so we measured depth in its direct vicinity. However, we agree that if the floating carpet is huge, an additional head loss will occur further upstream and can be important to take into account for the design of side dykes for instance. This will be specified by adding the following sentences: “The water depth measured was thus representative of the flow conditions in the direct vicinity of the open check dam. The longitudinal additional head loss related to LW accumulating further upstream of the ultrasonic sensors was not studied, although it would be important to take it into account for the design of side embankments (see the approach proposed by Di Risio and Sammarco, 2019 on this point).”

Reviewer Comment: 29. Add here or in a subsequent section information regarding tested discharge, to what flood they correspond and why you tested those values.

Thanks for the suggestion. The following information will be added : “Water discharge was measured with an electronic flow meter (accuracy ±0.01 l/s). It varied in the range 0-8.5 l/s, i.e., covering a wide range of discharge magnitude. This peak discharge of 8.5 l/s would then be equivalent to 54 m^3/s (using the scale ratio of 1:34), i.e., a discharge much higher than the Combe de Lancey 100 years return period peak discharge of 35 m^3/s. In essence, we intended to test not only project design events (*sensu.* Piton et al., 2019c), corresponding to 100-300 years return period events (5.5-7 l/s at model scale), but also safety check events (≈1000 years return period – 8.5 l/s at mode scale) to verify the structures’ behaviour when experiencing events of higher magnitude.”

Reviewer Comment: 30. L157: How did you choose the respective LW dimensions; please add quantitative information to the text instead of "twofold greater number of elements".

We will add this information in the revised paper : “LW logs are equivalent to logs with length of 1.6-6.6 m at scale ratio 1:33, i.e., not extremely long logs that are prone to be released over the dam. The distribution of sizes was arbitrarily decided based on field measurements obtain by the second author on his case study of Horiguchi et al. (2015).

Reviewer Comment: 31. L161: Regarding the fine material: how much organic fine material did you add, why did you choose pine needles, I assume this is very difficult to collect at the end; if you upscale pine needles using a scale factor of 30 it represents rather twigs.

Very relevant remark. We will add the following remark in the revised paper : “mixtures labelled “B” also included fine material, here fresh pine tree needles, that are somehow equivalent to twigs at real scale. The fine material mass was typically of 5-10% of the cumulated log mass. We did not include a model equivalent of leaves as Schalko et al. (2018, 2019a). Such material would have percolate through the LW jams and densify it, thus increasing in some extent the head losses (see discussion at section 5.1 on this topic).”

Although we agree that we were not on the conservative side on this topic, we believe that it has only a side effect since the relative head loss we measured are consistent with the results of Schalko et al. (2018, 2019a) who address this topic in much more detailed way. This will be discussed at section 5.1.

Reviewer Comment: 32. L167: In addition to the authors' experience, please include references to clogged LW volume at structures during previous floods or refer to previous flume experiments.

We will rephrase the sentence as follow : "Such amount of LW is typically found in open check dams after strong flood event (see e.g., data compiled by Piton, 2016, p. 66) and is sufficient to strongly disturb open check dam functioning (Shima et al., 2015, Tateishi et al., 2020)."

Reviewer Comment: 33. L189: See general comment regarding reference to Piton et al. 2019b

Suggestion taken into account as previsously noted.

Reviewer Comment: 34. ***Results:***

Reviewer Comment: 35. L213ff: please also comment on the effect of flow condition on this process; please see description of LW accumulation process at racks by Schalko et al. 2019 WRR - it is very similar and worthwhile to compare

Thank you for the suggestion. The key difference with the work of Schalko et al. (2019) and several other work of ETHZ is that we used varying water discharge while most works published so far were focusing on jam formation under steady discharge. Anyway, we will add in the revised paper the following sentence: "More detailed description of the formation of LW jam can be found, e.g., in Schalko et al. (2009a) under constant water discharge."

Reviewer Comment: 36. L290: Regarding the surface waves: Why did you not add a floater or flow straightener to suppress surface waves - how can this test be included if the initial conditions cannot be compared to the other tests?

We had problems with the energy dissipation at the inlet when the pumps were working at full power in the initial set up. An adaption was made before launching the run with LW to better dissipate energy. In our opinion, the tests can be included in the dataset because they were performed mostly to check the validity of the equation for pure water conditions and the fit is very good for discharges lower than 4.5-5 l/s.

Reviewer Comment: 37. L292: How was this problem fixed for the measurements with LW?

The volume of the upstream tank where pumps discharged was increased to better dissipate the kinetic energy from the pipe.

Reviewer Comment: 38. L324: See general comment on Schalko et al. (2019, Water Resources Research) stating that "The initiation of a LW carpet formation corresponds to the state, where the buoyancy force is higher than the downward drag force." Please add reference

Thanks for the suggestion. Indeed, the descriptions was yet present in Schalko et al. reference will be added here.

Reviewer Comment: 39. How did the authors account for the effect of organic fine material? Did you include the dimensions of the pine needles in an average "equivalent log diameter"?

Good point. No, the mean log diameter is determined only for coarse elements. We will add the following sentence: "Where, $D_{LW,mean.}$ is the mean log diameter of the LW mixture (m) determine only for LW elements (diameter > 0.1 m in the field, taken as 3 mm in our case assuming a scale ratio of 1:33)."

Reviewer Comment: 40. Figure 11: I agree that the data provide information that h decreases with increase T/Fd ratio, but the variations are extremely high; please discuss.*

We will discuss it but really, to our opinion, we should abandon the habit and hope that one can compute one single accurate value of water depth in an open check dam experiencing an extreme flood event. Working with range of uncertainties should become the standard way.

Here we will add the following sentence and add more element in the discussion: "Random variation in the log arrangement made the threshold h* value varying around the mean trend. Such stochasticity must be accepted as part of the process of LW jamming and behaviour."

Reviewer Comment: 41. ***Discussion***

Reviewer Comment: 42. See general comment regarding comparison with other studies

Agree, we will do it.

Reviewer Comment: 43. L375: Please clarify; Given the same approach flow depth, resulting backwater rise under supercritical conditions is higher because of the increased flow velocity and hence increased energy head.

Thanks for the suggestion. We will take it into account.

Reviewer Comment: 44. L377: What are "average LW volumes", these classifications are based on previous flume experiments and do not correspond to measured LW volumes in the field. I advise to use specific volume numbers or base such categories on field observations.

Good suggestion. We will rather use the dimensionless volume of LW suggested by Schalko et al. (2019) to provide a quantitative and comparable assessment.

Reviewer Comment: 45. L379: If you use the term kinetic energy then please use "potential energy" and not height; but I would recommend to use terminology that reflects your equation. In addition, this is not only the case for supercritical flow, but also for subcritical flow. Also, in L98 you state that F varied between 0.01 and 0.3, which is subcritical. Please revise.

Correct. We will rephrase the sentence.

Reviewer Comment: 46. L391: The authors observed that the LW accumulation piled up? Would you not say that the initial logs block the open flow cross-section, and logs are pulled downward along the dam?

Right, downward but also upward when increasing the discharge. We really think that the jam formation is slightly different than when using steady discharge. This sentence seek to explain that if the opening are more jammed, then the crest will also be more jammed, so we do not mention the drowning component.

Reviewer Comment: 47. L415: Due to the characteristics of LW it should not be recommended to use 1D models when simulation the interaction between LW and infrastructures. Since the paper is very long, I would recommend deleting this section and add the application of the approach in the Conclusions section.

We do not really agree with Reviewer #1 on this point. Works by Gschnitzer et al. (2017, Geomorphology) describe fairly well that in narrow and regular torrent bed, the bulk effect of LW can be taken into account with simple methods. The simple equations of Schalko et al. (2019) are even simpler than 1D models. In addition, we think important to stress that our T/Fd number has a much broader potential than the sole question of open check dam and LW. The section being quite short (160 words) we would like to keep it.

Reviewer Comment: 48. L435: See general comment regarding uncertainty – to apply the ratio between buoyancy and drag force, the backwater rise or resulting flow velocity is required. This depends on beta1 and beta2, which exhibit large fluctuations. Please comment.

The section will be adapted according to our response to the general comment.

Reviewer Comment: 49. ***Conclusions***

Reviewer Comment: 50. L458: The increase in flow depth includes a wide range - how should this then be considered by engineers?

See response to general comment. Working with a mean value of flow depth should be avoided in our opinion. It is more rigorous to acknowledge the random variability of the process and to bound the structure behaviour with scenarios.

Reviewer Comment: 51. ***Technical comments***

Reviewer Comment: 52. ***Abstract***

Reviewer Comment: 53. What is a piedmont river?

Wikipedia definition: "In physical geography, **piedmont** denotes a region of foothills of a mountain range. "

Reviewer Comment: 54. ***Introduction***

Reviewer Comment: 55. L30: "LW might actually play a significant role…"; please revise as several previous floods demonstrated the destructive power of LW accumulation at river infrastructures.

Done.

Reviewer Comment: 56. L35: Replace "disturbing" with affecting

Done

Reviewer Comment: 57. L55: Revise the two research questions, as they are very difficult to read in the present form. As described above, I advise that the authors use "hydraulic losses" instead of "energy dissipation". In addition, I would recommend replacing "bridge jamming hazards" with a more generic term as "flood related and structural hazards"

Thanks for the suggestion.

Reviewer Comment: 58. L62: Recommend using "poles" or simply "racks" instead of piles as these terms were also used in the cited papers.

Thanks for the suggestion.

*Reviewer Comment: 59. **Computing open check dam discharge capacity***
Reviewer Comment: 60. L96: Add flow depth to h and energy head to H

Ok, done.

Reviewer Comment: 61. L105: Add reference

Ok, done.

Reviewer Comment: 62. L107: Add h1 to Fig. 1

Well, we prefer not to add h1 because it varies depending on the dam type as explained in the paragraph just after Eq. (4).

Reviewer Comment: 63. L126: Revise sentence and refer to section instead of "see later".

Ok, rephrase and enhanced.

*Reviewer Comment: 64. **Materials and Methods***

Reviewer Comment: 65. L132: Either state one model scale factor or the range; in addition, please replace "to the authors' opinion" with a reference or remove it.

We first state that the range 1:20-1-60 is relevant to our opinion but use a 1:34 scale to provide field equivalent throughout the paper.

Reviewer Comment: 66. L144: than instead of that

Done, thanks.

Reviewer Comment: 67. L150: figure? Not clear

Rephrased.

Reviewer Comment: 68. L158: Check document regarding “error”

Done, thanks.

Reviewer Comment: 69. L161: The authors use the term “large wood” in the title and ms; I advise to only use this term and replace “debris” and “coarse debris”.

We mostly stick to the LW term however, woody debris is still widely used in the literature on hazard mitigation and is more concise than other formulation. We would like to keep the term.

Reviewer Comment: 70. L177: “to the flow” instead of “in the flow”

Done, thanks.

Reviewer Comment: 71. L177ff: Revise description on how the LW was added to the flow. “The LW jam could thus always grow up if flow conditions allowed it.” This is not clear.

We rephrased this passage and remove this particular sentence.

Reviewer Comment: 72. Figure 4: The scheme is very helpful; the data points are very informative, but to improve readability I recommend to only plot data of e.g., 2 LW mixtures and data without LW.

We added the whole mixture in the Figure only when all data are taken into account, i.e., when computing Beta max and min. It would be less clear if we plot only two mixtures and say that we compute the min and max only on these two mixture, wouldn’t it?

Reviewer Comment: 73. L196: Add “data” to point transparency

Done, thanks.

Reviewer Comment: 74. ***Results:***

Reviewer Comment: 75. L200: Include section numbers or delete this summary

Done, thanks.

Reviewer Comment: 76. L203: what are "most runs"?

Well, phase 3 of overtopping was not observed on several run with the Sabo dam because our pumps were not powerful enough. Anyway, we remove 'most'.

Reviewer Comment: 77. L204: "LW accumulation at check-dam" not against

Ok, done.

Reviewer Comment: 78. L205ff: Specify orientation and location of log (e.g.: in a horizontal position to the flow direction" or simply horizontal to the flow direction). In addition, revise: "They get stuck against and often parallel to the dam."

Ok, done.

Reviewer Comment: 79. L210: Please specify "in the LW jamming"

Ok, done.

Reviewer Comment: 80. L219: Revise "overflowing on the spillway" and check used prepositions in entire ms

Ok, done.

Reviewer Comment: 81. L222: "few LW pieces finding a way over the spillway", please revise, e.g. "few logs were transported over the spillway"

Ok, done.

Reviewer Comment: 82. L234: Delete "Nonetheless" or combine the subsections and make it clear to what "nonetheless" refers to.

Ok, done.

Reviewer Comment: 83. L239: If this was not tested or observed, please revise this sentence. e.g. it can be hypothesized and not "without any doubt".

Ok, done.

Reviewer Comment: 84. Figure 5: Please add flow direction arrows, and specify “most runs”

Ok, done.

Reviewer Comment: 85. Figure 6-9 and related text sections: See comment regarding “debris” and general comment regarding effect of LW dimensions on backwater rise.

See previous responses.

Reviewer Comment: 86. L270: delete “really”

Ok, done.

Reviewer Comment: 87. L276: close to each other not from

Ok, done.

Reviewer Comment: 88. L276: not clear what is meant by “current lines”

Sorry, wrong traduction, we meant streamlines. Now corrected.

Reviewer Comment: 89. L303: three instead of some

Modified.

Reviewer Comment: 90. Equation 5: please add definition of z2 again

Ok, done.

Reviewer Comment: 91. L312: maximum instead of max

Ok, done.

Reviewer Comment: 92. Figure 10: The different sizes of data points corresponding to release of LW are very helpful in Figure 11, but I would use same size for this Figure since the parameter corresponds to the x-axis.

Ok, done.

Reviewer Comment: 93. L322: Please revise, difficult to follow (LW submerged in number and tightly entangled?)

Revised.

Reviewer Comment: 94. L327: differentiate instead of “discriminate”

Ok, done.

Reviewer Comment: 95. Equation 7: I recommend using rho_LW instead of rho_s to avoid confusion with sediment density

Good idea, done.

Reviewer Comment: 96. L332: Recommend using V instead of u in Equation for consistency; based on the number of symbols a “Notation” section would be very helpful.

Ok, done.

Reviewer Comment: 97. L341: Delete “sucked” or replace

Ok, done.

Reviewer Comment: 98. L352: Close to the threshold

Ok, done.

Reviewer Comment: 99. ***Discussion***

Reviewer Comment: 100. L363: I agree but it is somewhat strange to write this sentence in the section "comparison"; you may want to move it to “Conclusions”

Ok, done.

Reviewer Comment: 101. L365: represents instead of "encapsulates"

Ok, done.

Reviewer Comment: 102. L367 ff: exhibit instead of experience

Ok, done.

Reviewer Comment: 103. L374: approaching instead of incoming flow

Ok, done.

Reviewer Comment: 104. L383: dams

Ok, done.

Reviewer Comment: 105. 398: Revise "thus flow power to stuck LW against the dam"

Ok, done.

Reviewer Comment: 106. Table 2: What is meant by "marginal release"; definition of LW volume categories not clear; 540 dm^3 were added in Schalko et al. compared to 75 dm^3 in Schmocker and Hager

Quantitative values using Vs,rel as proposed by Schalko et al. will be use.

Reviewer Comment: 107. L403: Please revise, not clear.

The section was rewritten.

Reviewer Comment: 108. L430: Revise "fruit"

Ok, done.

Reviewer Comment: 109. L444: differentiate instead of discriminate

Ok, done.

Reviewer Comment: 110. ***Conclusions***

Reviewer Comment: 111. L450: Please revise; what is "the other hand"; what are "transported element sizes" – logs?

Ok, revised.

Reviewer Comment: 112. L451: affect instead of "trouble"

Ok, done.

Reviewer Comment: 113. L465: What is meant by "without calibration" – see general comment on this transition

We meant that it has not been necessary to calibrate a given empirical parameter to compute T/Fd and obtain a regime change at the threshold value: Q, h and rho_LW,D_LW are measured and C_D is taken from the literature and the change indeed appear at T/F_D =1. Anyway, it is a detail and we removed the words.

We would like to profoundly thank reviewer #1 for this thorough and very constructive review. We feel lucky to benefit from the feedback of such an expert and rigorous review on our paper.

Comments by Reviwer #2

Reviewer Comment: 1. General comments:

Reviewer Comment: 2. I carefully read the manuscript titled "Open check dams and large wood: head losses and release conditions" submitted by Piton and co-authors to the Journal Natural Hazards and Earth System Sciences and currently undergoing a thorough open discussion process. The authors tackle a subject of utmost interest describing the behavior of large wood (LW) at variously designed open check dams, assessing quantitatively the increase of energy dissipation and thus the flow level at the structure due to accumulating of LW in various fashions and attempting to decipher the LW release mechanisms which may trigger subsequent hazard processes potentially resulting into severe damages at farther downstream located risk hotspots. In investigating these topics, the authors applied an experimental approach and conducted an extensive research program. This enabled them on *the one hand to gain important insights into the physical processes of LW entrapment and overtopping and to provide for estimates of the relative overtopping flow depths which may prove useful in engineering design endeavors. In light of these preliminary considerations the covered contents fit into the range of scopes of the Journal further contributing to improve our understanding of both the interplay of LW with instream structures and the potent hazard triggers which may result from this interaction.*

We thank very much Reviwer #2 for his time and comments.

Reviewer Comment: 3. As clearly emerges from the previous paragraphs I value the proposed research and the experimental approach which underpins it, I also contend that the employed experimental setup (i.e. inclined channel featuring constant width with an "insertion" of instream structures of different geometries and designs) might not reflect the entire variety of topographic settings real retention basins and check dam structures are inserted in. If the width of the channel was variable and if, in particular, the available retention volume for all constituents of wood laden flows increased behind the interfering instream structure, LW could be accommodated differently in space due to a more variable spectrum of flow patterns. Different longitudinal profiles (i.e. milder slopes in proximity to the check dam if compared with possibly steeper feeding channels) could also influence the LW accumulation upstream of the considered instream structure. Hence, I motivate the authors to comment of these issues, since the interested reader needs to clearly understand the limits of knowledge transfer related to your findings.

We agree that the pattern of accumulation and development of the LW carpet would change depending on the basin width rather than just the open check dam width. Regarding the effect of basin slope, the key question is how long is the dam backwater area? This is already discussed in the responses to the comments of Reviewer #1. Regarding the basin width we will add the following elements about this question: "The flume was 6.0 m long, 0.4 m wide and 0.4 m deep. Our flume modelled a basin 8-24 m wide (assuming scale ratio of 1:20-1:60) which is not extremely wide but consistent with many structures observed in the field (Piton et al., 2015, p. 22). The eventual widened basin located upstream of open check dam was thus not modelled. Experiments recently performed on an open check dam with a wide basin demonstrated that LW naturally floats spanning the whole basin width and accumulates in the close vicinity of the open check dam (Roth et al., *in press*). This was also observed in our relatively narrow flume. We hypothesize that using a wider basin would simply enable the LW to accumulate more widely rather than longitudinally along the flume. More complicated basin shape would likely trigger recirculation pattern that might modify the floating carpet behaviour far from the dams (see e.g., Tamagni et al. 2010). This work clearly focuses on the interaction between LW and open check dam in the close vicinity of the barrier. "

Reviewer Comment: 4. I also argue that the way how LW is approaching the interfering instream structure may co-determine the blockage behaviour. It could have been insightful to explicitly consider the peculiarities of LW influenced flow regimes rather than trying to supply LW to make the jam "supply unlimited" as is stated by the authors. To reiterate on this point, I think that the LW pieces arrival scenario may play a relevant role. The LW congestion (sensu Braudrick et al., 1997) or more recently described hyperconcentrated LW flow regimes (Ruiz-Villanueva et al., 2019) might play a crucial role in determining the blockage mechanisms, rightly due, as the authors point out, to both drag forces and buoyancy, to particular entanglement mechanisms between LW pieces and to friction forces between LW and exposed structure surface. I think that in their discussion the authors should deal with these issues and based on their findings provide hints for specific future research.

Reviewer Comment: 5. More generally I'm also convinced that the experimentally simulated discharge vs time relation (i.e. flow hydrograph) could indirectly exert an influence on the LW blockage and overtopping behavior. Falling limb scenarios seem not to be considered in the applied experimental protocol.

We agree that the question of how LW transported in various regimes approach open check dams is of interest. As pointed by Review #2 in his previous comment, the upstream channel features and shape as well as the basin features might also influence and modify the way LW approach structures. It is a complex question. In the material and method, we will introduce the following comment:

"The mixtures were progressively introduced to the flow from the first step. Logs were introduced manually at the upstream end of the flume, by groups of 5-15 logs, in a semi-congested mode (*sensu* Ruiz-Villanueva et al. 2019). Indeed, D'Agostino et al. (2000) reported that congested LW clusters tend to be laminated by the hydraulic jump that might appear where the channel flows enter the dam backwater area. In addition, congested LW clusters might also be reorganized by the recirculations that appear in the dam backwater area (see e.g., Tamagni et al., 2000). Consequently, although this is a simplification, we neglected the upstream, in-channel LW flow regime and forced a semi-congested supply regime."

And in the discussion we will add the following elements :

"This work modelled the rising limb of hydrographs until overtopping of LW or maximum pump capacity. Hydrograph recession or eventual flood hydrograph with several peaks were not modelled. LW jams tend to remain in place when discharge decreases according to our experience (see also Roth et al., *in press*). If LW jam are not cleaned, we consider, consistently with Schalko et al. (2019a), that large head losses are to be expected at structures already jammed by LW. Similarly, it is worth mentioning that if LW hypercongested flows (*sensu* Ruiz Villanueva et al. 2019) occur and enter the dam backwater area as a floating carpet comprising several layers of logs; it could reach the dam en masse and immediately form a 3D dense jam even though the flow remains in the floating carpet regime. In such a case, we hypothesize that the jam would be more stable than a single-layer floating carpet (i.e., would be released for higher overflowing depth) but this is to be verified in further works. The eventual effect of basin shape or presence of sediment deposit on the LW supply regime would also be worthy of investigation. "

Reviewer Comment: 6. To conclude this general comments section, I also share most of the concerns raised by the other anonymous reviewer. So without any further redundancy, I suggest a major revision focusing on the aforementioned both content and form related issues.

See responses to Reviewer #1.

Reviewer Comment: 7. Additional specific comments:
Reviewer Comment: 8. Abstract: L11: It would be better to rephrase "Large wood (LW) tends to accumulate against such structures" to "Large wood (LW) tends to accumulate at such structures".

Ok, done.

Reviewer Comment: 9. L14: It would be advisable to rephrase "to estimate how high is the overflowing depth atop the structure" to "to estimate the overflowing depth at the structure".

Ok, done.

Reviewer Comment: 10. L19: "is about 3-5 the mean log diameter". I'd write "is about 3-5 times (or D) the mean log diameter".

Ok, done.

Reviewer Comment: 11. L23-25: Please check this last sentence and enhance its readability.

We will certainly try something.

Reviewer Comment: 12. L26 Keywords: I'd put Large Wood instead of Woody Debris.

We used LW throughout the paper but wanted to use another key word for people calling it woody debris to find the paper. The term is still widely used by some communities.

Reviewer Comment: 13. 1 Introduction:
Reviewer Comment: 14. L70: Please reformulate the entire sentence to improve its readability.

Ok, done.

Reviewer Comment: 15. 2 Computing open check dam discharge capacity
Reviewer Comment: 16. L102: Check the font of z2 in the figure caption. It seems not to be consistent with other mathematical symbols.

Thanks, this will be corrected.

Reviewer Comment: 17. L104: The caption of Figure 1 should end with a full stop.

Ok, done.

Reviewer Comment: 18. L111:√2g is a common factor and it may be brought outside the bracket. The same suggestion applies to the second term in equation 4.3

Good suggesiton. Done.

Reviewer Comment: 19. Materials and Methods
Reviewer Comment: 20. L134: Instead of referring the reader to the research report of Piton et al. (2019b) please provide a sketch of the flume. Instead, please try make the difference of this work with respect to the cited research report explicit.

We will make clear that this report is in French and was not peer-reviewed. The flume is a simple flume and does not, to our opinion, deserve to the sketched. The paper has already many figures and it would be probably useless.

Reviewer Comment: 21. 3.3. LW mixtures
Reviewer Comment: 22. It would be an added value to provide more background on reasons for the selection of these specific mixtures.

Some more elements will be presented about the way we designed the mixture.

Reviewer Comment: 23. L158: There seems to be an inconsistent link to the figures in the supplementary material: (Figure 3 and Erreur ! Source du renvoi introuvable.-3 in supplementary material). Please fix it.

Yes, sorry for that. We will fix this point.

Reviewer Comment: 24. 3.4. Experimental protocol
Reviewer Comment: 25. L174-175: Is there a deeper logic for the choice of the number of runs. Are these numbers sufficient to capture the randomness of the LW jam formation?

Good question. Who knows? We think it sufficient to capture a first approximation of the randomness of the processes. And 3-4 repetitions are better than none. We will however add the following comment: "This is less than the high number of repetitions required to capture behaviour of single logs at reservoir dam spillways (Furlan et al., 2019, 2020) but we assume it sufficient to capture the random variation of the process of large amount of logs piling up at dam. This should be validated in later works."

Reviewer Comment: 26. L190: h0 seems to be in the wrong format. Homogenize with the other employed mathematical symbols.

Thanks, corrected.

Reviewer Comment: 27. Caption of Figure 4: The caption of this figure should be expanded to explain how to interpret the wealth of information displayed in the figure.

The new caption will be: “Computation steps for β1 and β2. Step 0: fit of the pure water equation. Step 1: computation of β1. Step 2: computation of bounding values of β1. Step 3: computation of β2. Step 4: computation of bounding values of β2. “

Reviewer Comment: 28. L204: I’d change “accumulation against: : :” into “accumulation at: : :”. Maybe even more rigorously “accumulation upstream of..”

We replaced "against" by "at" throughout all the paper where relevant.

Reviewer Comment: 29. L247: 4.2 LW-related head losses and stage –discharge relationships. Insert a space after –

Thanks, corrected.

Reviewer Comment: 30. L268: Change “both coefficient” into “both coefficients”

Thanks, corrected.

Reviewer Comment: 31. 4.3. Release conditions

Reviewer Comment: 32. L307-308: Furlan (2019) also studied the effect of log density that was ignored in this study. I think this should be explained. Is density unimportant? If yes, why?

Very relevant remark. We will add the following comment : "Furlan (2019) also studied the effect of log density that was ignored in this study. While the density is key to determine the submerged part of a single log floating and eventually passing over a dam reservoir spillway, as soon as several logs piles up and eventually slide or rotate over the open check dam crest, we assume that their respective density has only a side effect. It is however taken into account in the second dimensionless number introduced below.”

Reviewer Comment: 33. Figure 10: Personally, I find the figure a bit cryptic. On the horizontal axis “the fraction of large wood released is considered. In the legend the % released with circles of different sizes in displayed. Is there a redundancy here? Please explain.

The figure will be redrawn without the size and transparency dependency. It was redundant.

We thank very much reviewer #2 for his/her constructive comments and time spent in helping us to improve this work. It is really valuable.

Open check dams and large wood: head losses and release conditions

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Abstract.

Open check dams are strategic structures to control sediment and large wood transport during extreme flood events in steep streams and piedmont rivers. Large wood (LW) tends to accumulate ~~against~~at such structures, ~~to~~ obstruct their openings and ~~to~~ increase energy head losses, ~~dissipation~~ ~~and~~ thus~~,~~ increasing flow levels. ~~far~~The extent to which the stage discharge relationship of a check dam is modified by LW presence was so far not clear. ~~To which extent open check dams' stage-discharge relationships are consequently modified by LW presence was not clear so far.~~ ~~key~~Two questions needed to be addressed ~~This question is key~~ (i) ~~to estimate~~ how much bedload transport might be trapped in the related backwater areas and (ii) the overflowing depth at the structure~~to estimate how high is the overflowing depth atop the structure~~. Sufficiently high flows ~~might~~ may ~~These flows, when sufficiently high, might~~ trigger a sudden release of the ~~previously~~ trapped LW with eventual dramatic consequences downstream. This paper provides experimental quantification of LW-related ~~energy dissipation~~energy head loss and simple ways to compute the related increase in water depth at dams of various shapes: trapezoidal, slit, slot and SABO (i.e., made of piles), with consideration to the ~~including~~ flow capacity through their open body and atop the spillway. In addition, it~~It~~ was ~~additionally~~ ~~It was additionally~~ observed that LW is often released over the structure when the overflowing depth, i.e., depth above the spillway, is about 3-5 times the mean log diameter~~is about 3-5 the mean log diameter~~. Two regimes of LW accumulations were observed~~:~~. D~~d~~ams with low permeability generate low velocity upstream and LW then accumulates as floating carpets, i.e., as a single floating ~~single~~ layer. Conversely, dams with high permeability maintain high velocities ~~to~~immediately upstream of ~~close to~~ the dams and LW tends to ~~jam~~ accumulate ~~them~~ in dense complex 3D patterns. This is because the drag forces are stronger than the buoyancy ~~and~~ allowing the logs to be ~~are~~ sucked below the flow surface. In such cases, LW releases occur for higher overflowing depth and the LW-related head losses are higher. A new dimensionless number, namely the ~~ratio~~ buoyancy to drag force ratio can be used~~, enables~~ to compute whether (or not) flows stay in the floating carpet domain where buoyancy prevails on drag force.

Key words: woody debris; drifwood; head losses; ~~hyper-~~congested large wood transport; torrent control

1 Introduction

Open check dams, also called debris basins (Dodge, 1948), SABO dams (Ikeya, 1989; Mizuyama, 2008), torrential barriers (Rudolf-Miklau and Suda, 2013) or debris racks (Schmocker and Hager, 2013), are key structures in the mitigation of hazards related to solid transport, i.e., sediment and large wood (Piton and Recking, 2016a, 2016b). Large wood, hereafter "LW", is defined as logs thicker than 0.1 m and longer than 1 m (Braudrick et al., 1997). Extreme flood events occurring in forested catchments involve water, and sediment but also LW (Ruiz-Villanueva et al., 2019). The same authors demonstrated that LW may be transported in several regimes: un-congested (single logs not touching each other), congested (logs touching each other moving in groups), semi-congested (mix of un-congested and congested) or hyper-congested (many logs touching each other, accumulating on several layers and spanning the entire channel width). Although extreme flood events are first related to large amounts of water, LW ~~might~~ regularly~~actually~~ play a significant role in flood hazards by clogging bridges and ~~disturbing~~ affecting hydraulic structures, thus aggravating flooding and sediment deposition (Mazzorana and Fuchs, 2010; Mazzorana et al., 2009; Ruiz-Villanueva et al., 2014b; Schmocker and Weitbrecht, 2013, Chen et al., 2020). In rivers equipped with dams or bridges that are prone to ~~be~~ clogging~~ed~~ by LW, it is ~~thus~~ required to either (i) adapt these structures to prevent~~avoid the~~ clogging or (ii) trap LW ~~recruited~~ gathered during extreme floods before it reache~~d~~s the sensitive structures. Open check dams are relevant options to achieve this objective in torrents and piedmont rivers (Comiti et al., 2016; Wohl et al., 2016, 2019).

Open check dams aim to trap~~at trapping~~ all or part of the sediment and/or LW from ~~during~~ floods or debris flows (Hübl and Fiebiger, 2005). Scientific works that aim to ~~aiming at~~ better understand~~ing~~ how sediment is~~may be~~ trapped in open check dams are numerous (Armanini et al., 1991; Dodge, 1948; Ikeya, 1985; Reneuve, 1955; Zollinger, 1985);~~,~~ see the review of Piton and Recking (2016a). One key conclusion was that an increased water depth at the dam~~ passage,~~ induces a low velocity area in the backwater behind the dam ~~backwater~~ where bedload is usually~~might be~~ trapped. Computing the stage-discharge relationship is thus a critical design step to assess the sediment-trapping efficacy.

Studies on interactions between LW and open check dams started more recently, in the late 1980s in Japan (Ishikawa and Mizuyama, 1988; Ishikawa, 1994; Kasai et al., 1996; SABO Division, 2000; Uchiogi et al., 1996), and later in the 2000s in Europe (Bezzola et al., 2004; D'Agostino et al., 2000; Lange and Bezzola, 2006). These works mostly focused on trapping efficacy and on defining relevant opening sizes and shape to achieve ~~appropriate~~ the desired function~~ing~~. Numerical modelling of LW freely floating or interacting with structures emerged in the 2010s and is in constant improvement (Horiguchi et al., 2015; Kimura and Kitazono, 2019; Ruiz-Villanueva et al., 2014a; Shrestha et al., 2012).

Field observations complement~~e~~ the~~se~~ laboratory and numerical studies~~works~~: Bezzola et al. (2004) in particular reported examples of open check dams mal~~dys~~function~~s~~ing in the presence of LW. They proposed options to adapt existing works notably by adding grills upstream of slit and slot dams. Shima et al. (2015, 2016) also reported ~~key~~ effects of LW presence in the functioning of open check dams in Japan. The topic of interactions between LW and open check dams was reviewed by Piton and Recking (2016b). Two scientific questions in particular remained insufficiently ~~covered~~answered: (i) how much LW does it take to increase~~s~~ ~~energy dissipation~~energy head loss ~~and thus the flow level~~ at a structure ~~by~~through the obstructi~~ng~~on of the flow section? and (ii) which conditions drive the sudden downstream release of LW accumulated by the structure when the structure is overtopped, thus dramatically aggravating flood-related and structural hazards ~~bridge jamming hazards~~?

The first question has been~~was yet~~ addressed for reservoir dams: for ogee crest spillways with piles by Hartlieb (2012, 2017), Schmocker (2017), and Pfister et al. (2020) and for piano-key weirs (PK-weirs) by Pfister et al. (2013b). It was also recently thoroughly covered by the hydraulic research team of ETH Zürich for rack structures made of po~~i~~les (Schalko 2020, Schalko et al., 2018, 2019a, 2019b; Schmocker and Hager, 2013; Schmocker and Weitbrecht, 2013; Schmocker et al., 2014). ~~Recent experiments by Rossi and Armanini (2019), Meninno et al. (2019) and Chen et al. (2020) also explored trapping efficacy of slits dams, without and eventually with upstream grills as suggested by Bezzola et al. (2004).~~ All these works describe comprehensively how LW accumulates ~~against~~at barriers. In addition, they proposed methods to compute the head losses related to LW accumulating ~~against~~at racks. Despite the high randomness of the processes, it was demonstrated that approaching flow conditions (e.g., Froude number, flow depth, water discharge) and features of the LW mixtures (LW volume, LW diameter, presence of fine material as branches and leaves) ~~were demonstrated to~~ drive LW-related head losses.

The second question~~ of~~, i.e., which conditions drive ~~of~~ LW ~~releases during~~ overtopping and releases over structure was only addressed ~~only by authors working on~~for reservoir dam spillways: Pfister et al. (2013a) for PK-weirs, as well as Furlan et al. (2018, 2019, 2020)~~ and~~, Furlan (2019) and Pfister et al. (2020) for ogee crests with piles. These studies~~works~~ concluded that the ratio of flow depth to LW diameter was key to ~~discriminate~~ determining whether ~~either~~ LW stays in the reservoir or overtops the dam. The ratio of LW length to opening ~~pile interval~~width is also a contributing factor as seen in ~~was also known from~~ SABO and slit dam experiments (Ishikawa and Mizuyama, 1989, Shrestha et al., 2012, Horiguchi et al., 2015, Chen et al. 2020). Recent experiments by Rossi and Armanini (2019), Meninno et al. (2019) and Chen et al. (2020) also explored the trapping efficacy of slits dams, without and eventually with upstream grills as suggested by Bezzola et al. (2004). ~~Works~~ Experiments on racks and slit dams did not address the question of LW overtopping because the modelled structure were not overtopped (D'Agostino et al. 2000, Schmocker and Hager, 2013; Schmocker and Weitbrecht, 2013; Schmocker et al., 2014, Schalko et al., 2018, 2019a, 2019b, Rossi and Armanini 2019, Meninno et al., 2019, Chen et al., 2020). The authors merely reported high trapping efficacy (>90%) for the tested racks and that trapping efficacy ~~varying~~ varies with slit width and the interval between upstream grill bars. ~~It is c~~Consequently, it is not clear which conditions drive the release of LW above open structures such as SABO, slit, slot or trapezoidal dams. One could hypothesize that results from dam reservoir spillways might be transferable to open check dams. However flow conditions upstream of open check dams, e.g., higher Froude number or effect of openings, may~~ight~~ partially modify the jamming and release processes.

Since water depth above the structure seems to be a key driver of both sediment trapping and LW release, this paper seeks first to provide a way to compute water depth at structures in the presence of LW, and secondly to study the conditions driving the release of the trapped elements. This paper explores both questions experimentally. It is organized in four sections and a conclusion: first, the hydraulic computation of water stage – discharge relationships is ~~first~~ presented, second the experimental apparatus used is ~~secondly~~ described and third the results are ~~thirdly~~ presented and, fourth, ~~-~~finally discussed. Throughout this paper, ~~we try to consistently use~~ the term “overflowing” is used when speaking about the water passing over the dam, and ~~rather~~the term “overtopping” when referring to the passage of LW over the dam.

2 Computing open check dam discharge capacity

Stage-discharge relationships were used according to the state-of-the-art (Piton and Recking, 2016a, 2016b) with the ~~.~~ ~~In~~ addition~~,~~ of a ~~–~~dimensionless coefficients called β_i (-) ~~were~~ introduced to account for the LW-related ~~energy dissipation~~energy head loss. The relationship between water depth over the slit or slot bottom, with LW, noted h (m), water depth ~~-~~without LW noted h_0 (m), LW-related head loss noted Δh (m) and β_i is as follow (see notations in Figure 1~~Figure 1~~):

$$h = h_0 + \Delta h = h_0\left(1+\frac{\Delta h}{h_0}\right) \quad \Leftrightarrow \quad h_0 = \frac{h}{\left(1+\frac{\Delta h}{h_0}\right)} \quad \underset{h\approx H}{\Longleftrightarrow} \quad \frac{\Delta h}{h_0} = \beta_i \tag{1}$$

with ~~-~~$H = h+V^2/2g = h(1+Fr^2/2)$ the flow ~~energy~~energy head (m), V the flow velocity (m/s), g the gravitational acceleration (9.81 m/s²) and $Fr=V/(gh)^{0.5}$ the Froude Number (-). ~~It is worth~~ R~~r~~ecall~~ing~~ that the depth h should be replaced by ~~energy~~energy head H in stage-discharge relationships wherever the approximation $h \approx H$ is wrong (Piton et al., 2016), e.g., for $Fr > 0.3$ if one accepts a 5 % difference on the hypothesis $h \approx H$. We find this uncertainty reasonable regarding the complexity of flow in mountain rivers. Since a~~A~~ll runs ~~with LW~~ performed with LW for the present paper ~~a~~have ~~re in the range 0.01 <~~ F~~-~~$r < 0.3$; h is ~~thus~~ used in the stage-discharge relationships.

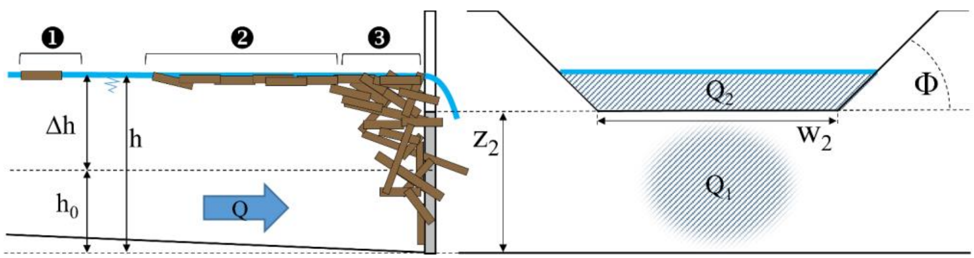

Figure 1. Notation used throughout the paper: a) side view of LW jamming a barrier and b) front view of barrier. Water depth without LW and with LW are denoted h_0 and h, respectively. The difference between h and h_0 is the head loss Δh. Dam crest is of height z_2. Logs may be (1) freely flowing, (2) floating in a single layer as a carpet or (3) jamming the barrier with most pieces submerged. The total water discharge Q is split into Q_1 the discharge passing through the dam and Q_2 the discharge overflowing the dam.

For the flow passing through the dams Q_1 (m³/s)~~-~~, the Grand Orifice equation was used (Piton and Recking, 2016a):

$$Q_1 = N\mu_1 W_1 \frac{2}{3}\sqrt{2g}\left(\left(\frac{h}{1+\beta_1}\right)^{1.5} - \left(\frac{h-h_1}{1+\beta_1}\right)^{1.5}\right) \tag{2}$$

Where N is the number of similar openings (-), μ_1 is the orifice coefficient (-), W_1 is the opening width (m), h_1 is the opening height (m) and β_1 is a coefficient to account for LW-related head losses on discharge *passing through the dam* (-). If flow depth h is lower than the orifice height h_1, the second term is removed and the equation is a simple slit flow equation.

The spillway capacity Q_2 (m^3/s) is computed using a trapezoid weir equation (Deymier et al., 1995, p.70):

$$Q_2 = \mu_2\sqrt{2g}\left(W_2\cancel{\sqrt{2g}}\left(\frac{h-z_2}{1+\beta_2}\right)^{1.5} + \frac{0.8}{\tan\Phi}\cancel{\sqrt{2g}}\left(\frac{h-z_2}{1+\beta_2}\right)^{2.5}\right) \quad (3)$$

Where μ_2 is the weir coefficient (-), W_2 is the spillway horizontal width (m), z_2 is the spillway level (m), β_2 is another coefficient to account for LW-related head losses *in flows overflowing the dam~~barrier~~* (-) and Φ is the angle between horizontal and the wing crest (45° in our experiments).

In the absence of LW, the c~~C~~oefficients β_i are set to zero~~ in the absence of LW~~, and formula returns to its ~~the formulation then being the~~ classical formulation~~one~~. Using β_i=0.6 means for example that compared to pure water flow, the flow depth will increase by 60 % to convey the same water discharge through the LW ~~accumulation~~ accumulated over the same dam. Although it is quite similar, its reading and interpretation is more straightforward than providing direct estimation of Δh (which is dimensional and discharge-specific) or ~~modification~~ modifying the~~of~~ discharge capacity ~~weir or orifice coefficients~~ as e.g., USBR (2013)~~the 30% reduction proposed by CFBR (2013)~~ for reservoir dam spillways~~, for which computation is required to know the related stage increase~~. The dam total capacity Q (m^3/s) is computed by summing Eqs. (2) and (3).

$$Q = Q_1 + Q_2 = \mu_1 W_1 \frac{2}{3}\sqrt{2g}\left(\left(\frac{h}{1+\beta_1}\right)^{1.5} - \left(\frac{h-h_1}{1+\beta_1}\right)^{1.5}\right) + \mu_2\sqrt{2g}\left(W_2\cancel{\sqrt{2g}}\left(\frac{h-z_2}{1+\beta_2}\right)^{1.5} + \frac{0.8}{\tan\Phi}\cancel{\sqrt{2g}}\left(\frac{h-z_2}{1+\beta_2}\right)^{2.5}\right) \quad (4)$$

It is worth noting that the Grand Orifice equation is used to compute discharge through the dam even for slit and SABO dams, i.e., structures ~~that are precisely~~ not~~ structures~~ equipped ~~-~~with orifices, but rather gap-crested~~ structures~~. For the gap-crested dams with slits, we used $h_1 = z_2$, i.e., the orifice height is the same ~~than~~ as the slit height. Doing so, ~~we compute separately~~ the discharge passing through the dam Q_1 (computed with β_1) is computed separately from and the discharge overflowing the structure above the slit top ~~in~~ Q_2 (computed with β_2). This option ~~We selected this option~~was selected because the ~~relative energy loss~~relative energy head losses are greater~~bigger~~ in flows passing over the structure (i.e., the one passing through the floating jam), than in flows passing through the structure (see section 5.2~~1.1later~~). In other words, in the presence of LW~~ logs floating~~, the ~~energy dissipation~~energy head loss is higher in the discharge over the weir than in discharge passing through the slit, i.e., $\beta_2 > \beta_1$.

3 Material and methods

3.1 Flume and sensors

The experimental setup is not a downscaled version of any particular site. ~~It is somewhat representative of a 1:30 scale model and s~~Scale ratio in the ranges 1:20-1:~~40~~ 60 remains relevant. To provide field equivalent of our model results, ~~to the~~

~~authors' opinion~~a scale ratio of 1:34 is used throughout the paper and is relevant with the case study of the Combe de Lancey stream (Piton et al., 2019c, Roth et al., *in press*). Any upscaling should be performed using the Froude similitude. The experimental setup is presented ~~more~~ in more detail in the research report of Piton et al. (2019b). The flume ~~was 6.0 m long, 0.4 m wide and 0.4 m deep. Its~~ adjustable slope was set ~~at~~to 0.02 m/m for all experiments. This slope is relatively low but is commonly observed in bedload retention basin (Piton et al. 2015, p. 22). This slope is the order of magnitude of channel slopes in alluvial fan distal reaches, i.e., the slope used for the design of guiding channels that are increasingly used in open check dams (Schwindt et al., 2018, Piton et al., 2019c). In addition, since the open check dams triggered high backwater rise and subcritical flow regime, the bottom flume slope is of secondary importance: flow conditions are controlled by the open check dam. The flume was 6.0 m long, 0.4 m wide and 0.4 m deep. Our flume modelled a basin 8-24 m wide (assuming scale ratio of 1:20-1:60) which is not extremely wide but consistent with many structures observed in the field (Piton et al., 2015, p. 22). The eventual widened basin located upstream of open check dams was thus not modelled. Experiments recently performed on an open check dam with a wide basin demonstrated that LW naturally floats spanning the whole basin width and accumulates in the close vicinity of the open check dam (Roth et al., *in press*). This was also observed in our relatively narrow flume. We hypothesize that using a wider basin would simply result in LW accumulating more widely rather than longitudinally along the flume. More complicated basin shape would likely trigger recirculation patterns that might modify the floating carpet behaviour far from the dams (see e.g., Tamagni et al. 2010). This work clearly focuses on the interaction between LW and open check dam in the close vicinity of the barrier.

The tested dams were installed at the downstream end of the flume, perpendicular to its bottom. Flow depth was measured at a frequency of 10 Hz by an ultrasonic sensor located 0.2~~20~~ ~~c~~m upstream of the dams (accuracy ±1 mm). The water depth measured was thus representative of the flow conditions in the direct vicinity of the open check dam. The mean value ± standard deviation of the Froude number was 0.04 ± 0.01, 0.06 ± 0.02, 0.1 ± 0.02 and 0.24 ± 0.08 for the closed, slit, slot and Sabo dam, respectively (see section 3.2 for dams names and features). The additional head loss related to ~~.~~LW accumulating further upstream of the ultrasonic sensors was not studied; although it would be important to take it into account for the design of side embankments (see the approach proposed by Di Risio and Sammarco, 2019 on this point), it would be irrelevant to take it into account for the design of the dam itself.

Water discharge was measured with an electronic flow meter (accuracy ±0.01 l/s). It varied in the range 0-8.5 l/s, i.e., covering a wide range of discharge magnitude. This peak discharge of 8.5 l/s would then be equivalent to 54 m³/s (using the scale ratio of 1:34), i.e., a discharge much higher than the Combe de Lancey 100 years return period peak discharge of 35 m³/s. In essence, we intended to test not only project design events (*sensu.* Piton et al., 2019c), corresponding to 100-300 years return period events (5.5-7 l/s at model scale), but also safety check events (≈1000 years return period – 8.5 l/s at model scale) to verify the structures' behaviour when experiencing events of higher magnitude. Water discharge was increased in steps ~~by step~~. An automatic system adjusted pump~~s~~ velocities to achieve the targeted discharge. Each water depth or discharge measurement provided in the following is computed as the mean value of~~n~~ a time step lasting 1-4 minutes. These averaging time windows started once~~when~~ flow depth ~~was stable~~stabilized after the transient period related to the change from one discharge step to another, and stopped just before the discharge was changed again. Standard deviations of discharge and flow depth were also computed and later used as a proxy for~~of~~ the uncertainty on each measurement. Error bars are displayed on plots wherever uncertainties, computed using~~after~~ quadratic error propagation, were high enough such that the error bars were bigger than~~t~~ dots. LW released during each step ~~were weighted on a scale~~, as well as, the total LW sample at the end of each run, were weighted on a scale. LW releases were arbitrarily considered as "significant" if the mass released during one step was more than 10% the weight of all LW used in the experiment.

3.2 Dams

A selection of the most common check dams encountered in France and Japan was tested (Horiguchi et al., 2015; Piton et al., 2019a): (i) closed-type dam ~~figuring~~ representing a ~~check dam~~ recently dredged check dam, (ii) slit dams with horizontal grills, (iii) slot dams with five openings and (iv) SABO dams with 11 openings would mimic ~~that could figure~~ the ~~widely used steel pipes~~rack dams very common in Japan. The shape and size of dams tested are provided in Figure 2~~Figure 2~~. All dams have a crest set at z_2 = ~~55~~ 50 mm and level datum for depth and energy head computation is taken at opening bottom, or 50 mm below the crest for the closed dam. ~~They~~ Dams were made of transparent Plexiglas plates, ~~10~~ 10 mm thick and numerically cut.

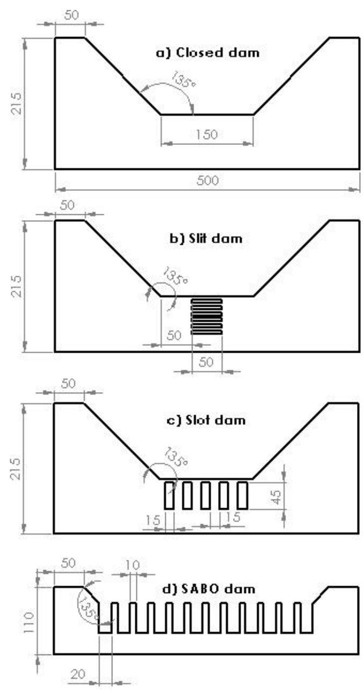

Figure 2. Dam tested a) closed dam, b) slit grilled dam, c) slot dam and d) SABO dam

3.3 LW mixtures

Five different mixtures of LW, called 1A, 1B, 2A, 2B, 3B, were prepared with fresh *Sorbus Aucuparia* stems of ~~length 50 mm, 100 mm, 150 mm and eventually 200 mm (Table 1) and~~ various diameters (Figure 3 and ~~Figure 3 and~~ Figure S1-3 in supplementary material) and of 50 mm, 100 mm, 150 mm and eventually 200 mm length (Table 1– equivalent to logs with length of 1.6-6.6 m at scale ratio 1:33, i.e., logs not extremely long and thus particularly prone to be released over the dam). The distribution of sizes was arbitrarily decided based on field measurements obtain by the second author on his case study of Horiguchi et al. (2015). The wood relative density was measured in the range 0.745-0.83 with an average of 0.77. Mixtures numbered “1” and “2” had maximum log length of 200 mm and 150 mm, respectively. Mixtures labelled “A” only consisted of coarse debris, i.e. logs, while mixtures labelled “B” also included fine material, here fresh pine tree needles, that are somehow equivalent to twigs at real scale. The fine material mass was typically of 5-10% of the cumulated log mass. We did not include a model equivalent of leaves as Schalko et al. (2018, 2019a). Such material would have percolate through the LW jams and densify it; increasing in some extent head losses (see discussion at section 5.1 on this topic).~~.~~ Mixture 3B was prepared

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to test the effects of a higher LW supply. It ~~was merely twice the mass of mixture 1B, i.e.~~ contained ~~roughly twofold greater number of elements~~507 logs (against 250 in mixture 1B), had a maximum log length of 200 mm and included fine material~~. Mixture 3B was prepared to test more intense LW supply~~. Overall, the solid volumes tested were high but not extreme. At scale 1:34 for instance, t~~T~~hey would be equivalent ~~for instance at scale 1:30~~ to ~~27~~30-~~54~~ 80 m^3 of solid volume in a reach ~~12~~ 13 m wide, which would be ~~79~~60-~~270~~ 400 m^3 of LW jam assuming ~~jam porosity~~compactness coefficient ~~-~~(i.e.,~~ 1 - solid volume/~~total jam volume / solid log volume) from ~~66~~-2% to ~~80 %~~5 ~~(Lange and Bezzola, 2006)~~(Lange and Bezzola, 2006, Schalko et al., 2019a). Such amount of LW ~~is sufficient~~ is typically found in open check dams after strong flood event (see e.g., data compiled by Piton, 2016, p. 66) and is sufficient to strongly ~~disturb~~ affect open check dam functioning ~~to the experience of the authors~~ (Shima et al., 2015, Tateishi et al., 2020).

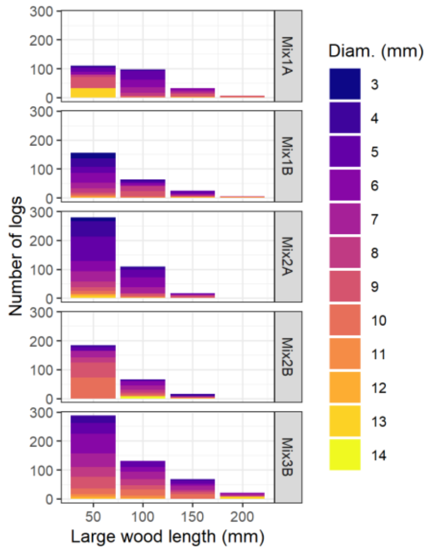
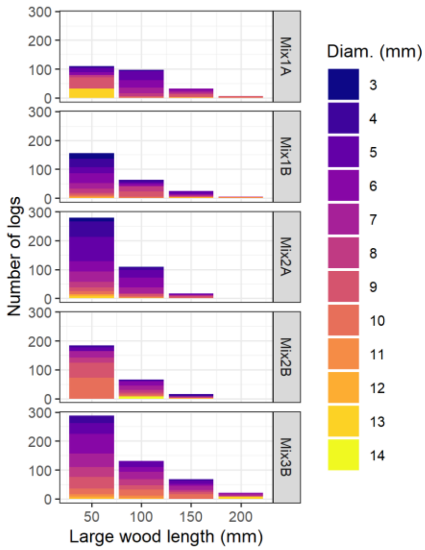


Figure 3. Number, length and diameter of coarse debris composing the LW mixtures

Table 1. LW mixtures features

Mixture name	Number of logs by length (mm)				Fine material (pine needles)	Mean length (mm)	Mean diameter (mm)	Solid volume (10^{-3} m^3)
	50	100	150	200	FM	$L_{LW,mean}$	$D_{LW,mean}$	V_S
MIX 1A	114	88	31	**7**		87	7.8	1.04

MIX 1B	160	64	25	**5**	**Yes**	76	6.5	0.77
MIX 2A	279	11	16	-		67	6.2	0.94
MIX 2B	186	65	15	-	**Yes**	83	8.3	1.01
MIX 3B	332	131	65	**20**	**Yes**	82	7.4	**2.04**



~~**Figure 3.** Number, length and diameter of coarse debris composing the LW mixtures~~

3.4 Experimental protocol

For each dam, two to three runs were performed in pure water conditions to check the repeatability of the experiment and to calibrate the orifice and weir coefficients, μ_1 and μ_2, respectively. Three to four runs with each LW mixture were then performed to capture the random variation of LW jam formation, thus resulting in 15 to 20 independent runs with varying mixtures for each dam. This is less than the high number of repetitions required to capture behaviour of single logs at reservoir dam spillways (Furlan et al., 2019, 2020) but we assume it sufficient to capture the random variation of the process of large amount of logs piling up at dam. This should be validated in later works. In ~~E~~each run the discharge was progressively increased in steps of ~~Each run consisted in a progressive increase in the discharge by~~ 0.2~~—~~0.5 L/s, starting ~~steps~~ from 0.5 L/s, to full overtopping and the release of all floating LW. The mixtures were progressively ~~manually~~ introduced to~~in~~ the flow at each~~from the first~~ step. Logs were introduced manually at the upstream end of the flume, by groups of 5-15 logs, in a semi-congested mode (*sensu* Ruiz-Villanueva et al. 2019). Indeed, D'Agostino et al. (2000) reported that congested LW clusters tend to be laminated by the hydraulic jump that might appear where the channel flows enter the dam backwater area. In addition, congested LW clusters might also be reorganized by the recirculations that appear in the dam backwater area (see e.g., Tamagni et al., 2000). Consequently, although this is a simplification, we neglected the upstream, in-channel LW flow regime and forced a semi-congested supply regime.

Acknowledging that LW recruitment and transfer is quite random in the field (Comiti et al., 2016), we did not try to define a relevant rate of LW introduction in the flume as done in other works (e.g., D'Agostino et al., 2000, Meninno et al., 2019 or Rossi and Armanini 2019). An inverse approach was rather chosen trying to supply LW to make the jam "supply unlimited". We hypothesized that LW transported by the approaching or recirculating flows, i.e. LW of type (1) in Figure 1~~Figure 1~~, generates marginal ~~energy dissipation~~energy head loss. Conversely, LW of type (2) and (3) in Figure 1~~Figure 1~~, does not move, generates obstruction and friction with the flow and thus participates in ~~energy dissipation~~energy head loss. During experimental runs, it was made sure to always~~ to~~ have LW of type (1) in the flume until LW mixture was entirely supplied. ~~The LW jam could thus always grow up if flow conditions allowed it.~~ The protocol was thus to follow the rule "LW is to be added whenever all elements are stuck to the dam and no more elements are freely (re)circulating~~es~~". During each discharge step, we continuously checked that at least a couple of logs were recirculating and we introduced more of them whenever it was not the case. This protocol has the advantage of avoiding mechanisms related to specific LW recruitments and transfer scenarios and is expected to prevent eventual side effects of making an arbitrary choice on LW supply rate.

The experimental data comprised~~s~~ of 649 flow depth and discharge measurements of which one quarter concerns pure water experiments and three quarters concern LW (data provided in supplemental data of this paper~~appendix of Piton et al., 2019b~~). The head loss Δh was computed as the difference between h, the depth measured with LW, and h_0, the depth computed in the pure water condition, i.e., using Equation 4 with the same discharge and setting $\beta_1 = \beta_2 = 0$. The β_i coefficients were then computed in several steps (Figure 4~~Figure 4~~): (i) β_1 was computed using Equation (2) for each measurement where no or slight overflowing discharge was observed, (ii) the bounds of β_1 were determined out of all these measurements, (iii) β_2 was computed using Equation (4) for all measurements considering β_1-bounds and their average and (iv) bounds of β_2 were ~~computed~~ fit on discharges that were strongly overflowing. Since β_1-bounds are calibrated for no and low overflowing while β_2 -bounds are calibrated on high overflowing, ~~points~~ the transparency of the points are increased on the f~~following f~~igures ~~are increased~~ where they lose relevance.

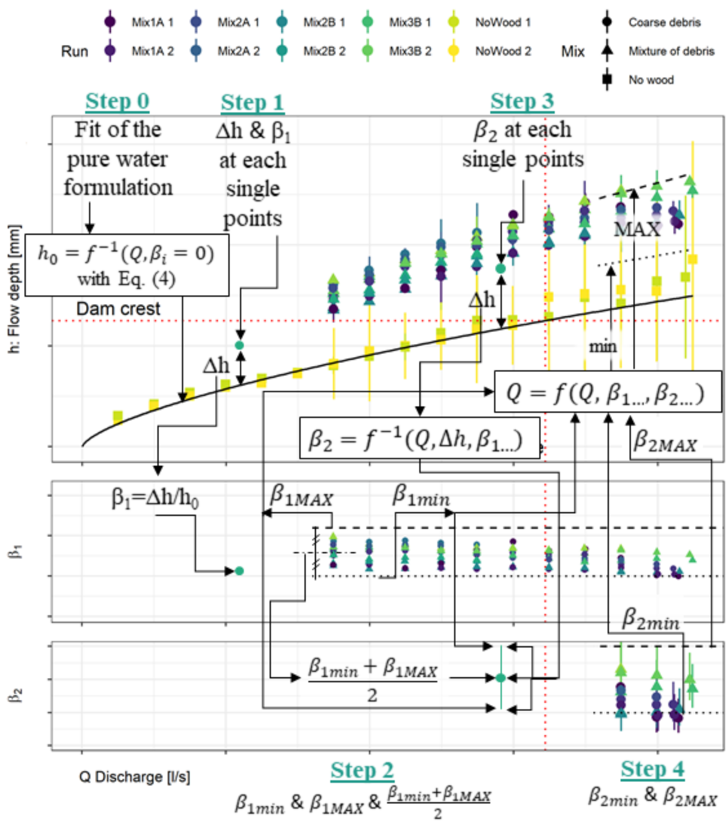


Figure 4. Computation steps for β_1 and β_2. Step 0: fit of the pure water equation. Step 1: computation of β_1. Step 2: computation of bounding values of β_1. Step 3: computation of β_2. Step 4: computation of bounding values of β_2.

4 Results

~~Results are organized in three sections: (i) a qualitative description of the interaction between LW and barriers, (ii) quantitative analysis of head losses in each dam and (iii) release conditions for all dams.~~

4.1 Main phases of LW jamming and releases

The same main phases of the process were observed during ~~most~~ runs with LW (Figure 5~~Figure 5~~).

4.1.1 Phase 1: accumulation ~~against~~ at the dam

During phase 1, LW approached the openings and a few pieces eventually passed through the dam (Figure 5~~Figure 5~~a-b). LW elements were mostly stuck against the dam, ~~approaching~~ generally floating in a horizontal position. Logs tended to be oriented parallel to the dam in its direct vicinity and to accumulate in increasingly random orientation when distance to the dam increased. ~~They get stuck against and often parallel to the dam.~~ At each discharge step, flow depth increased progressively up to a new stable value. The LW would reorganize~~d~~ at each flow depth change, generating ~~increasing~~ increased obstruction of the openings. ~~-~~LW stuck against the openings seldom moved upward ~~with~~ when ~~the~~ free surface level changed, but would rather stay~~ed~~ stuck at their position due to the drag force, the friction with ~~opening borders~~the dam and their eventual entanglement in the openings and between ~~in the LW jamming~~logs. Neighbouring elements could ~~thus~~ then approach the dam and openings for any sufficient water depth increase. They ~~were consequently~~ would ~~piling~~ pile up over other jamm~~ing~~ed LW pieces and would progressively obstruct~~ed~~ all the entire upstream face of the dam. LW elements not stuck ~~against~~at the dam were either (see figure 1): (1) Floating freely and moving with the flows, (2) ~~Organized~~ organized close to the dam in a quasi-immobile "floating carpet", or (3) ~~D~~dragged underneath the carpet, after impact ~~on~~ with the floating LW~~, and~~ reach~~ed~~ing the openings or get~~ting~~ting stuck against other logs. Logs of type (3) were more numerous when~~The latter required that~~ flow through the openings was significant, e.g., ~~and was consequently mostly observed~~ with the SABO dam, as well as with the slot dam, though in a lesser extent. Phase 1 was not observed on the closed dam since it had no openings. More detailed description of the formation of LW jam can be found, e.g., in Schalko et al. (2009a) under constant water discharge.

4.1.2 Phase 2: overflowing with possible LW release

Phase 2 started when overflow~~ing~~ over ~~on~~ the spillway reached a sufficient depth to (eventually) release some LW, i.e., when the flow depth approached or ~~passed~~ exceeded the LW diameter. The floating carpet followed the free surface level and was then in a position higher than the dam crest. The floating carpet arrangement was modified regularly ~~-~~ – most notably at increases of water depth - because of the impact of LW upstream or following the release of a few logs transported ~~few LW pieces finding a way~~ over the spillway (compare e.g., Figure 5~~Figure 5~~c-d and e-f). The floating carpet was in a position

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theoretically prone to be released during this phase but was usually not, due to the spillway obstruction by LW elements (i) arching the spillway, (ii) entangled in the openings or (iii) entangled in other submerged stable logs. In dams with small openings, i.e., the slit and slot dams, floating carpets could be quite extensive while lateral views demonstrated that the openings were jammed only by a few pieces (e.g., Figure 5~~Figure 5~~c-d). The SABO dam had such a large proportion of the flow that could pass through the dam that even when overflowed, newly supplied-LW were again regularly dragged underwater and fed the submerged jam.

Lower discharge passing through the dam ~~induced~~ encouraged lower number of LW to be submerged resulting in a~~and~~ more developed floating carpet. The LW elements obstructing the spillway were sometimes very stable, typically when arches formed or if one element took a vertical position, ~~protruded~~ protruding above the water surface thus behaving as a pole and offering a new point to form stable arches.

4.1.3 Phase 3: actual LW release

~~Nonetheless,~~ Phase 3 ~~consisting~~ consisted in sudden and massive releases of all floating LW either in a congested or hyper-congested regime with a wetted front (*sensu* Ruiz Villanueva et al. 2019). Phase 3 was systematically observed on the closed, slit and slot dams, but~~. Phase 3 was observed on the SABO dam~~ only three times on the SABO dam due to experimental limitation: the ~~maximal~~ maximum discharge capacity of the experimental apparatus of 8.9 L/s was only approaching the conditions for sudden releases. Releases occurred for higher discharges on the SABO dam because (i) the ratios between water depth and dam height were small due to the high permeability, thus limiting the overflowing ~~discharge~~ depth and (ii) the 11 openings enabled numerous pieces to become entangled and to protrude over the dam crest, thus creating numerous obstacles to the release of the floating elements. We believe that p~~P~~hase 3 would be observed on the SABO dam on all runs for sufficiently high discharge~~ without any doubt~~.

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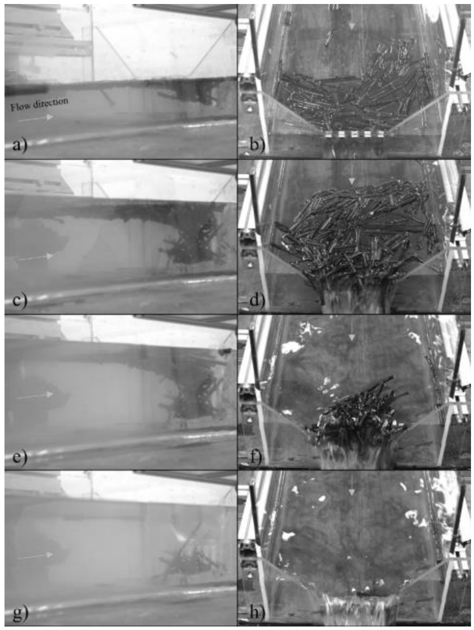

Figure 5 : Example of phases observed during ~~most~~ runs where overtopping occured (illustrated here with Mix A2, repetition #2 on slot dam) : Phase 1 – LW simply stuck ~~against~~at the dam, a few floating LW apart, here at discharge 0.5 L/s, (a) side view and (b) top view ; Phase 2 – slots jammed and floating carpet developed upstream, here at discharge 3.5 L/s, (c) side view and (d) top view ; Phase 2 later – denser jam for higher discharge (here at 5.4 L/s), several pieces yet released, (d) side view and (e) top view and, 5 second later the LW overtopped the barrier and Phase 3 – final state after jam overtopping occurs here still for discharge 5.4 L/s, (g) side view and (h) top view

4.2 LW-related head losses and stage – discharge relationships

The first objective of this paper is to provide a way to compute the increase in water depth eventually observed upstream of check dams in the presence of LW. The calibration of dimensionless coefficients of weir and orifice as well as coefficients β_1 and β_2 are provided in the next sections for each dam tested. Their intercomparison is later provided in the discussion.

4.2.1 Closed dam

The weir coefficient was calibrated at μ_2=0.4 based on the pure water runs (Figure 6~~Figure 6~~). This value was later re-used in Eq. (4) for all other dams. The value was calibrated on discharges higher than 1 L/s such that overflowing~~topping~~ depth was ~~higher~~ greater than 1.5 times the dam thickness and the narrow-crested weir hypothesis holds. Using Eq. (3) with β_2 = 0.05 and β_2 = 0.4, provide satisfying lower and upper bounds, respectively, of the 98 points measured with LW on the closed dam (Figure 6~~Figure 6~~). Coefficient β_2 was directly computed without approximation for this dam since determining the β_1 coefficient is not relevant due to the absence of an opening. A slight but not systematic decreasing trend in β_2 can be observed ~~when~~ with increasing discharge ~~increased~~ which is related to the LW accumulation rearranging as discharge increased. LW releases occurred mostly for discharge between 1.5 and 2.5 L/s, ~~thus the~~with few points for Q > 2.0 L/s.

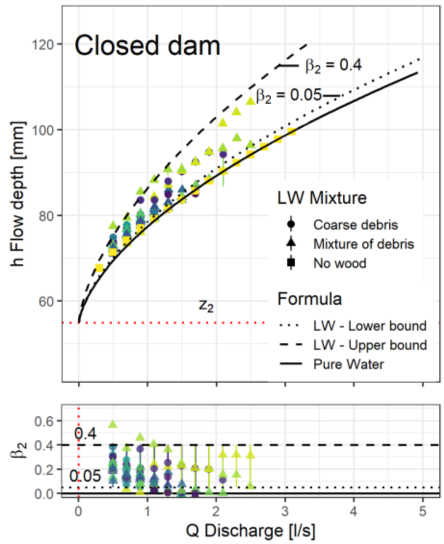

Figure 6. Flow depth versus discharge for closed dam and back-calculated β_2 values, each color shade corresponds to a different run

4.2.2 Slit dam

The orifice coefficient of the slit dam was calibrated at $\mu_1 = 0.42$, namely 65 % of 0.65, which is the value proposed for a single slit without grill by Piton et al. (2016). This result is consistent with the 50 % obstruction of the slit by the grill and the correction coefficient provided by Piton and Recking (2016a) for grilled slits. Using Equation (4) with $\beta_1 = 0.05$ and $\beta_2 = 0.2$ or $\beta_1 = 0.25$ and β_2=0.6, provides satisfying lower and upper bounds, respectively, of the 85 points measured with LW on the slit dam (Figure 7~~Figure 7~~). A few points related to one single run reached β_2 values that were slitghly higher. Both coefficients β_1 and β_2 show slight decreases with increasing discharge and are often maximum close to the transition between phase 1 and phase 2, i.e., when flow ~~starts really to overtop~~overflow the dam by more than 1-2 times the log diameter.

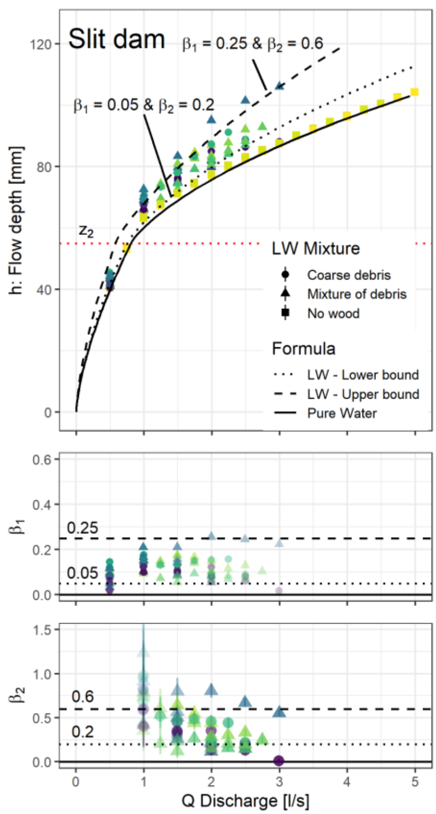

Figure 7. Flow depth versus discharge for grilled-slit dam and back-calculated β_1 and β_2 values, each color shade corresponds to a different run

4.2.3 Slot dam

The orifice coefficient of the slot dam was calibrated at $\mu_1 = 0.72$, i.e., 110% of the standard value of 0.65 proposed for a single slit. This is likely related to the influence of several orifices being in close proximity to one another~~close from each other~~. ~~lines~~It enables the flow ~~They enable current~~ streamlines to be more smoothly arranged and prevents~~ing~~ thethe ~~-current~~ streamlines of the central slots from being sharply angled ~~sharp angle for the current lines of the central slots~~ (see also SABO dam below). Using Equation (4) with $\beta_1 = 0.15$ and $\beta_2 = 0.2$ or $\beta_1 = 0.6$ and β_2=0.6, provides satisfying lower and upper bounds, respectively, of the 127 points measured with LW on the slot dam (Figure 8~~Figure 8~~). Both coefficients β_1 and β_2 show again slight decreases with increasing discharge and are again maximum close to the transition between phase 1 and 2~~, i.e., when flow starts overtopping the dam~~. It is interesting to note that the lower and upper values of β_2 are similar for the slit and the slot dams.

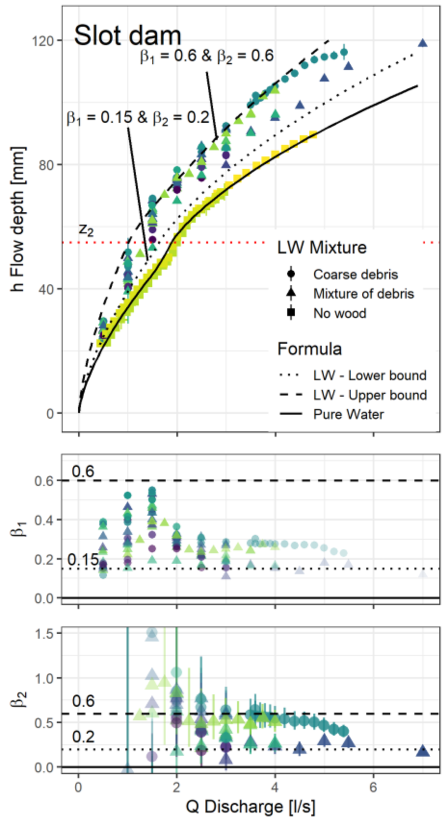

Figure 8. Flow depth versus discharge for slot dam and back-calculated β_1 and β_2 values, each color shade corresponds to a different run

4.2.4 SABO dam

The orifice coefficient of the SABO dam was calibrated at $\mu_1 = 0.81$, i.e., 125 % of the standard value of 0.65 for one single slit. With 11 openings, i.e., 6 more opening parts than the slot dam, the stream lines are likely to be even ~~even~~ better arranged ~~this~~and is a probable explanation for its increased ~~which probably explains this better~~ hydraulic capacity. During the pure water experiments, ~~S~~some experimental modification to the arrangement at the flume inlet ~~were~~ was necessary to enable ~~pushing~~ the pump capacity to be pushed to its maximum but waves appeared in the flume and greatly disturbed ~~greatly~~ the free surface level measurement. The visible high error bars for some runs ~~and especially the pure water ones~~ are an ~~artefact~~ artefact of these waves and the deviation from the theoretical curve for Q > 5.0 L/s should not be considered relevant. This problem was fixed on most measurements with LW with beneficial effect on the error bars. Using Equation (4) with $\beta_1 = 0.5$ and $\beta_2 = 0.5$ or $\beta_1 = 1.1$ and $\beta_2=2$, provides, respectively, satisfying lower and upper bounds of the 186 points measured with LW on the slot dam (Figure 9~~Figure 9~~). Both coefficients β_1 and β_2 show here again slight decreases with increasing discharge and are again maximum close to the transition between phase 1 and 2, i.e. when flow starts ~~overtopping~~ overflowing the dam which occur much later than for the other dams.

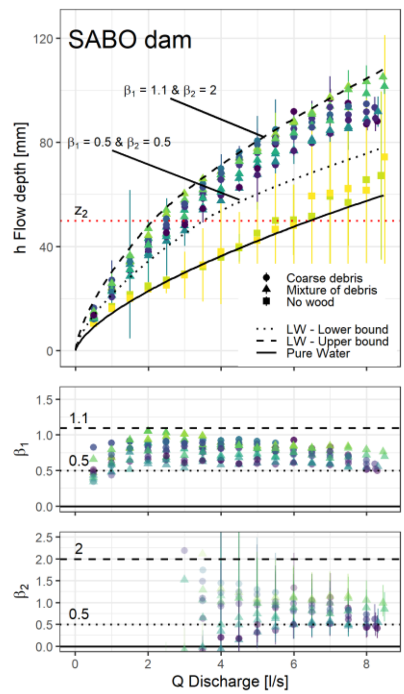

Figure 9. Flow depth versus discharge for SABO dam and back-calculated β_1 and β_2 values, each color shade corresponds to a different run

4.3 Release conditions

The second objective of this paper was to describe conditions leading to the release of LW downstream by dam overtopping. In order to transfer the results of this study, ~~some~~ dimensionless numbers can be~~were~~ defined to characterize the flow conditions and eventually the domain where LW releases were observed, i.e., where trapping efficacy drops suddenly. Furlan (2019) identified that the probability of logs to be trapped by reservoir dam spillways was first related to the ratio between overtopping depth and log diameter. The dimensionless overtopping depth ratio h^* (-) is ~~consequently~~ defined as~~by~~:

$$h^* = \frac{h - z_2}{D_{LW,mean}} \quad (5)$$

Where, h is the water depth (m), z_2 is the dam crest level (m) and $D_{LW,mean.}$ is the mean log diameter of the LW mixture (m) determined only for LW elements (diameter > 0.1 m in the field, taken as 3 mm in our case assuming a scale ratio of 1:33). ~~Furlan (2019) also studied the effect of log density that was ignored in this study.~~

Figure 10~~Figure 10~~ displays the percentage of LW released against h^*. It can be observed that most “significant” releases, i.e. >10%, occurred in the range 3~~.0~~ < h^* <5~~.0~~. A few releases were also observed for much higher overtopping ratios, up to h^* = 10. They occurred for LW jams stabilized by logs arching the weir or by logs tightly entangled in the submerged elements. The LW maximum length might play a marginal role for the closed dam and for the SABO dam where releases occurred more for mixtures with a smaller maximum length but this was not consistently observed for all dams. Log maximum lengths ~~being~~ of either 150 mm or 200 mm with a ~~and~~ weir base width of~~being~~ at least 150 mm wide, i.e. log length is longer than twice the weir width, creates conditions with very high probability of stable arching of weir (Piton and Recking, 2016b)~~, i.e., with log length longer than twice weir width~~. These conditions were not tested. Consequently, log length had~~was~~ only a marginal effect on release condition.

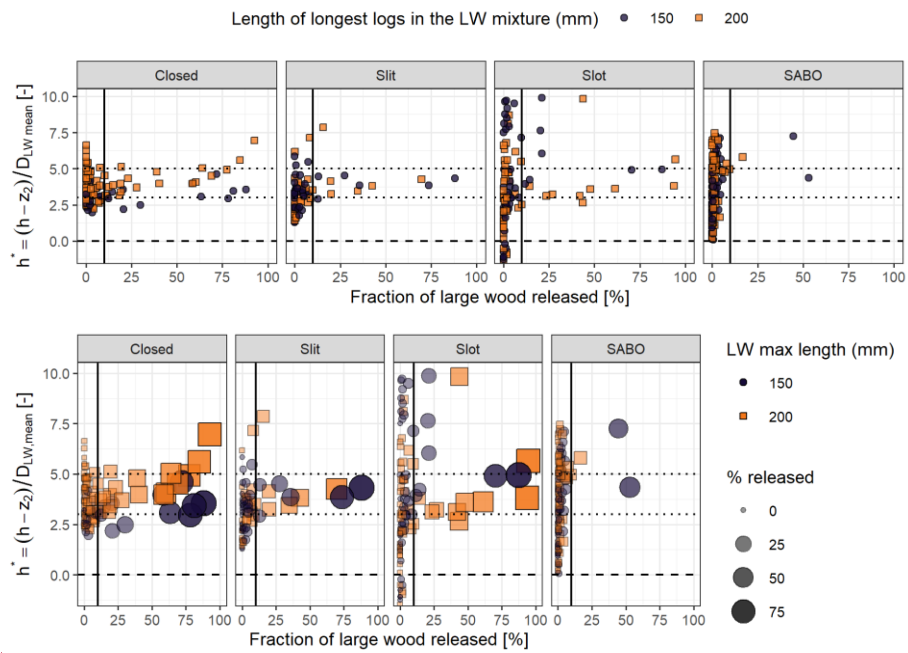

Figure 10. Percentage of LW released (i.e. mass fraction of LW released during one discharge step over total sample mass) against dimensionless overtopping depth h^*~~, dot size and opacity proportional to LW released~~. The continuous vertical line marked the 10% released that was fixed arbitrarily as the threshold value for significant LW release. Most -significant LW release appear for $3<h^*<5$.

Furlan (2019) also studied the effect of log density but that was ignored in this study. While the density is key to determine the submerged part of a single log floating and eventually passing over a dam reservoir spillway, as soon as several logs piles up and eventually slide or rotate over the open check dam crest, we assume that their respective density has only a side effect. It is however taken into account in the second dimensionless number introduced below.

~~dam~~The dimensionless overtopping ratio h^* was not sufficient to capture the overtopping process. Floating carpets (type 2 in Figure 1) were observed to be more easily released than LW jams that were submerged and tightly entangled (type 3 in Figure 1). Jams against the SABO dam ~~were~~ ~~The dimensionless overtopping depth h^* was not sufficient to capture the overtopping process. In essence, floating carpets (type 2 in Figure 1) were observed to be more easily released than LW submerged in number and tightly entangled (type 3 in Figure 1). Jams against the SABO dam were~~ for instance were rarely released even for $h^*>5$. As comprehensively described by Schalko et al. (2019a), ~~The balance between buoyancy and drag force governs~~ the shift from the regime of floating carpet to the regime of submerged jam is governed by the balance between buoyancy and drag force~~.~~s. Similar to ~~In the line of~~ Kimura and Kitazono (2019), a dimensionless number determining~~figuring~~ whether buoyancy or drag force dominates~~d~~ is hereafter defined in order to ~~discriminate~~ differentiate which kind of jam might form. Buoyancy, noted Π hereafter, was computed considering the logs ~~nearly to be submerged i.e. with their~~ full volume under water surface, i.e. at the transition between floating and sinking:

$$\Pi = \frac{g(\rho-\rho_{\cancel{s}LW})\pi D_{LW\,mean}^{2} L_{LW\,mean}}{4} \qquad (7)$$

~~With~~ Where ρ and ~~ρ_s~~ ρ_{LW} are the water and LW density, respectively (kg/m^3). The drag force F_D was computed using:

$$F_D = \frac{1}{2}\rho C_D D_{LW\,mean} L_{LW\,mean} \cancel{u} v^2 \qquad (8)$$

~~With~~ Where C_D is the drag coefficient (-) assumed ~~taken equal~~ to be equal to 1.2 for logs without branches (Merten et al., 2010; Ruiz-Villanueva et al., 2014a), and ~~u~~ v is the flow velocity near the log (m/s). This formulation relies on several hypotheses: (i) the log is aassumed to be ~~considered~~ in a transverse position with respect to the flow direction and quasi-submerged, consistent~~ly~~ with the hypothesis made for buoyancy, and~~thus~~ the surface of the log is~~being~~ proportional to its diameter times its length, (ii) the log is quasi-immobile so the full velocity of the flow is considered, (iii) the precise value of ~~u~~ v in the direct vicinity of the logs is unknown but the cross sectional averaged velocity is considered relevant as a first approximation thus ~~u~~ $v \approx$ ~~$V =$~~ $Q/(hW)$ where~~with~~ W is the flume width (here 0.4 m). ~~We define t~~The dimensionless number called buoyancy to drag force ratio Π/F_D is defined as the ratio between Eq. (7) and Eq. (8) that can be rearranged as follow:

$$\frac{\Pi}{F_D} = \frac{\pi}{2C_D}\frac{\rho-\rho_{\cancel{s}LW}}{\rho} D_{LW\,mean}\frac{g\cancel{W_{mean}^2}W^2h^2}{Q^2} = \frac{\pi}{2C_D}\frac{\rho-\rho_s}{\rho}\frac{D_{LW\,mean}}{h}\frac{1}{Fr^2} \qquad (9)$$

Theoretically, when Π/F_D >>1, a log ~~Theoretically, a log in a context where Π/F_D >>1~~ should float since buoyancy prevails, and that should be the "floating carpet domain". Conversely, when Π/F_D << 1, a log can be submerged, ~~sucked and~~ dragged by the flow below the water surface ~~in a context where Π/F_D << 1.0~~, and this~~which~~ should be the "piling jam domain". Figure 11~~Figure 11~~ displays Π/F_D versus h^* with the size of dots proportional to the amount of LW released. In addition, a smoothed trendline related only to points with released LW fraction higher than 10% was computed using the stat smooth function, loess method of the ggplot2 library in R (Wickham, 2016) and plotted in orange. This statistical fit overall confirms that most releases appeared for 3~~.0~~ <h^*<5~~.0~~, although it highlights particular behaviour for high and low values of Π/F_D. In the floating carpet domain, i.e., when Π/F_D >>1, the threshold value for overtopping of h^* is comprised in the range of 3-5~~,~~. The threshold however decreases slightly ~~decreasing~~ for Π/F_D > 3~~.0~~ and, for Π/F_D > 10, ~~approaching~~approaches the critical values of h*=1.5-2~~.0~~ identified by Furlan (2019) for dam reservoir spillways.

In the piling jam domain, i.e. when Π/F_D << 1~~.0~~, the few available observations suggest a significant increase in flow overtopping, h^* with decreasing Π/F_D (sharp breaking in trendline; more obvious on the inset of Figure 11). This is due to drag force being higher than buoyancy force, favouring piling up, dense 3D jams and strong friction between logs. Close ~~from~~ to the threshold, i.e. for $\Pi/F_D \approx$ 1~~.0~~, the range of 3~~.0~~-5~~.0~~ is still applicable. Random variation in the log arrangement made the threshold h* value varying around the mean trend. Such stochasticity must be accepted as part of the process of LW jamming and behaviour. In addition, a~~A~~s said before, a few points, related to randomly-generated very stable arrangements may reach higher values of h^*, e.g. the few black squares with $h^* \approx$ 6~~.0~~-7~~.0~~ related to jams retained by arching logs across the weir. Small transparent points appear for h^* <- 0 and are related to a few logs passing through the dams' openings.

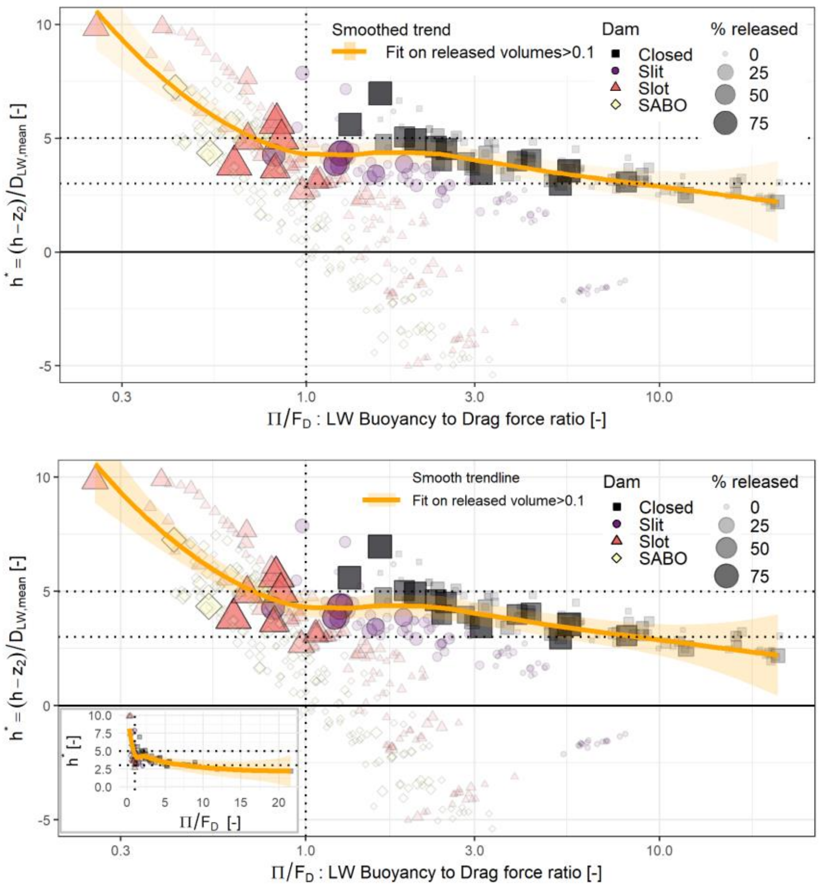

Figure 11: Dimensionless overtopping depth h^* VS buoyancy to drag force ratio Π/F_D with dot size and opacity proportional to the amount of LW released. Inset: same figure with non-logarithmic x-axis. ~~-~~Releases occur for lower h* in the Π/F_D >>1.0, i.e., if buoyancy prevails and floating carpets forms while releases occur for higher h^* if dense jams forms under high drag forces in the Π/F_D << 1.0 domain

5 Discussion

5.1 Comparison with existing studies

Past works on interactions between LW and dams studied LW-related head losses or trapping efficacy, which is somewhatat ~~i.e., somewhat~~ the opposite of release conditions (~~Table 2~~Table 2). ~~No works so far addressed in such details compound structures with both openings and an upper spillway as the present paper.~~ The results of the experiments presented in this paper are also included in Table 2 ~~Table 2~~ using $\Delta h/h_0$, which ~~encapsulates~~ represents the balance between Q_1 and Q_2 and thus effects of both β_1 and β_2. Values of $\Delta h/h_0$ measured in past works in quite different structures than the one tested in this paper are very consistent:

(i) overflowing structures as dam spillway, PK-weirs and our closed dam ~~experience~~exhibit the smallest $\Delta h/h_0$ values ranging in 0-50% (Hartlieb, 2012, 2017, Schmocker, 2017, Furlan, 2019, Pfister et al., 2013a, 2013b, 2020); with lower values when a rack or protruding piles a set upstream of the spillway (Schmocker, 2017, Furlan, 2019, Pfister et al., 2020);

(ii) slit and slot dams ~~experience~~exhibit slightly higher $\Delta h/h_0$ ranging in 5~~.0~~ %-60 % (Meninno et al., 2019) with lower values when grills protect the slit; and

(iii) widely open structures as SABO dam and racks ~~experience~~exhibit high values of $\Delta h/h_0$ ranging in 20 %-100 % (Horiguchi et al., 2015, Schmocker and Hager, 2013, Schalko et al., 2019a)~~,~~ , for subcritical approaching~~incoming~~ flows (up to 210 % as in the experiments of Schmocker and Hager, 2013, who used high LW volumes), and ranging in 170 %-230 % for supercritical ~~incoming~~ approaching flows (up to 330 % for high volume of LW - Schmocker and Hager, 2013).

Supercritical conditions results in very high $\Delta h/h_0$ because h_0 ~~are~~ is low. ~~, while their relative energy loss $\Delta H/H_0$ are of the same order of magnitude than for subcritical flows (see appendix for detailed computation of $\Delta H/H_0$).~~ Given the same approach flow depth, resulting backwater rise under supercritical conditions is higher because of the increased flow velocity and hence increased energy head. However, their relative energy head loss $\Delta H/H_0$ is of the same order of magnitude as it is for subcritical flows (see appendix for detailed computation of $\Delta H/H_0$). $\Delta H/H_0$ are typically up to 0.6-0.7 for average LW volumes and up to $\Delta H/H_0 \approx 1.5$ for high volume of LW. Using ~~relative energy loss~~relative energy head loss $\Delta H/H_0$ rather than relative head loss $\Delta h/h_0$ in future work is recommended since it removes the bias related to the lack of kinetic energy in the ratio $\Delta h/h_0$. In fact, most of ~~deed a key part of~~ kinetic energy transforms into potential energy (i.e., height) when fast flow (either ~~strongly~~ supercritical or subcritical) ~~flows~~ reaches ~~subcritical flows in~~ the vicinity of hydraulic structures jammed by LW.

The volume of LW used in the experiments was demonstrated to be a key parameter of the head loss (Schalko et al., 2018, 2019a). In order to compare results from many different works in Table 2, the ranges of dimensionless solid relative volume $V_{s,rel} = V_s/Wh_0^2$ was computed. It can be observed that it varies by several order of magnitude but does not seems to significantly affect the relative head loss providing that sufficient LW is used to clog the structure, which is consistent with the conclusion of Schmocker and Hager (2013), Schmocker (2017) or Schalko et al. (2019a).

The experiments of the present paper~~is work~~ modelled the rising limb of hydrographs until overtopping of LW or maximum pump capacity. Hydrograph recession or eventual flood hydrograph with several peaks were not modelled. LW jams tend to remain in place when discharge decreases according to our experience (see also Roth et al., *in press*). If LW jam are not removed, we consider, consistently with Schalko et al. (2019a), that large head losses are to be expected at structures already jammed by LW. Similarly, it is worth mentioning that if LW hypercongested flows (*sensu* Ruiz Villanueva et al. 2019) occur and enter the dam backwater area as a floating carpet comprising several layers of logs; it could reach the dam en masse and immediately form a 3D dense jam even though the flow remains in the floating carpet regime. In such a case, we hypothesize that the jam would be more stable than a single-layer floating carpet (i.e., would be released for higher overflowing depth) but this is to be verified in further works. The eventual effect of basin shape or presence of sediment deposit on the LW supply regime would also be worthy of investigation.

Table 2: Literature review of existing results on LW-related head losses and release conditions

Type of structure	Ranges of $\Delta h/h_0$ ($\Delta H/H_0$~~)*~~)[a] [Fr_0~~]**~~][b]	Range of $V_{s,rel} = V_s/(W h_0^2)$ [c]	Parameter driving LW ~~downstream~~ releases	Comment	Reference	Work main topic~~****~~ [d]
Piano-key weir	(0-0.2) Unknown Fr_0	0.2-80	h/D_{LW}>3 (h/D_{LW} >10 with branches and root wads)	$\Delta H/H_0$ up to 0.6 for low discharge	Pfister et al., 2013a, 2013b	HL
Reservoir dam spillway	0.05-0.5 [0,05~~ ; ~~-0.35]	0.04-0.7		Test begun with $h >> D_{LW}$	Hartlieb, 2012, 2017	HL
-	0.2-0.3 [0.5]	2-8		Without upstream rack	Schmocker, 2017	HL
~~Reservoir dam spillway~~ -	0-0.3 [0,01]	2-15	h/D_{LW}>1.5 W_0/L_{LW}>1.25		Furlan, 2019	TE
~~Reservoir dam spillway~~ -	0.~~0~~-0.29 [0.~~04~~01--0.~~1~~02]	12-522	h/D_{LW}>1.7-3 W_0/L_{LW}>1.3	Without piles	Pfister et al. 2020	HL & TE
	0-0.29 [0.02-0.1]	1-68	h/D_{LW}>1.7-3 W_0/L_{LW}>1.3	With piles	Pfister et al. 2020	HL
Closed check dam	0.05-0.4 [0.01-0.1]	0.3-1	5 > h/D_{LW} >3		This paper	HL & TE
Reservoir dam spillway	0.08-0.1 [0.5]	2-8		With upstream rack	Schmocker, 2017	HL
-	0.02-0.17 [0.02-0.1]	12-522		Piles protruding in the reservoir	Pfister et al. 2020	HL
-	0-0.06 [0.01-0.1]	1-189		With upstream rack	Pfister et al. 2020	HL
Slit dam ~~with inclined grill~~	0-0.1 [0.07]	0.002-0.08	Unknown ~~Unknown~~	*, with inclined grill located upstream~~Overtopping not possible~~	Meninno et al., 2019	HL & TE
~~Slit dam with grill~~ -	0.05-0.3 [0.05-0.1]	0.3-2	5 >h/D_{LW}> 3	With grill in the slit	This paper	HL & TE
Slit dam	0.05-0.6 [0.07]	0.002-0.08	W_0/L_{LW} > 1/2 ~~(for small LW discharge : 8-14 logs/s)~~ W_0 / L_{LW}>≈1 ~~(for high LW discharge : 150 logs/s)~~	* , 8-14 logs/s~~Overtopping not possible~~ at inlet *, 150 logs/s at inlet	Meninno et al., 2019	HL & TE ~~HL & TE~~
~~Slit dam~~ -	Unknown $\Delta h/h_0$ ~~head losses and Fr_0~~[1.5-4]	0.1-0.4	W_0 /L_{LW}>0.8-1	~~Overtopping not possible~~*, debris flow experiments	Chen et al., 2020	TE
Slot dam	0.05-0.6 [0.1-0.15]	0.2-11	6 >h/D_{LW}> 3		This paper	HL & TE
SABO dam	0.2-1 -(0.2-1) [0.4-0.5]	0.7-62	7 >h/D_{LW}> 4		This paper	HL & TE
~~SABO dam~~ -	0-1.2 [2.5-2.8]	1-15	W_0/L_{LW} > 0.5-0.75		Horiguchi et al., 2015	TE
Rack dam	1.0-2.1 (0.8-1.4) [0,5 ;0.8] 3.0-3.3- (0.9-1.1) [1.5]	5 2	Very good trapping efficacy (~~only 2 %-8 % of log pass through~~92%-98%)	~~Overtopping not possible*~~	Schmocker and Hager, 2013	HL ~~HL~~

~~Rack dam~~	0.3-1 (0.2-0.7) [0,3~~;~~ 0.75] 1.7-2.2 (0.5-0.6) [1.2~~;~~ 1.6]	0.3-23	Very good trapping efficacy (~~only 0 %-5 % of log pass through~~95%-100%)	~~Overtopping not possible~~*	Schalko et al., 2019a	HL ~~HL~~

[a] ~~*~~Ranges of $\Delta H/H_0$ are not provided when upstream Froude number Fr<0.3 because $\Delta H/H_0 \approx \Delta h/h_0$

[b]~~~~ Range of Fr in pure water condition, computed in the reservoir for spillways**

[c] On slit dams h_0 is taken as the depth approaching the slit without LW, on reservoir dam spillways the depth is computed on the spillway without LW, not in the reservoir

[d]~~**~~ HL: Head Losses; TE: Trapping Efficacy**

*** Overtopping not possible**

5.2 First step toward generalization

Four types of dams were tested in this paper. In order to transfer the results to other open check dam configurations, dam permeability was computed using Void Ratio (Di Stefano and Ferro, 2013), ~~namely~~ defined as the cumulated opening width normalized by the flume width *W* (m):

$$\text{Void ratio} = \frac{\sum_N W_1}{W} \tag{10}$$

Dams with higher permeability have higher void ratios, and ~~also~~ higher discharge passing through the dam. Therefore,~~; and thus~~ drag forces are greater to push~~stuck~~ LW ~~against~~at the dam, thus increasing the value of β_1 (Figure 12~~Figure 12~~a). Meanwhile β_2 also increase~~s too~~ because the dense jam created ~~against~~at the dam piles up and obstructs the dam~~barrier~~ crest ~~as well~~ (Figure 12~~Figure 12~~b). Consistently, the lower the permeability and ~~thus~~ the void ratio of the dam, the greater~~bigger~~ the initial water depth for a given discharge. A corollary is that higher water depth means slower flow and higher likelihood of ~~to~~ staying in the floating carpet regime, and~~thus~~ preventing piling up of LW ~~against~~at the dam and resulting in higher β_1 and β_2. The V~~V~~oid Ratio is obviously correlated with Π/F_D: high Void Ratio reduces *h* and thus Π/F_D (see Eq. 9). However, we do not provide a graph showing β_i against Π/F_D because water depth *h* is involved in the computation of both variables, thus generating spurious correlation in such a graph; a drawback that the Void Ratio does not have.

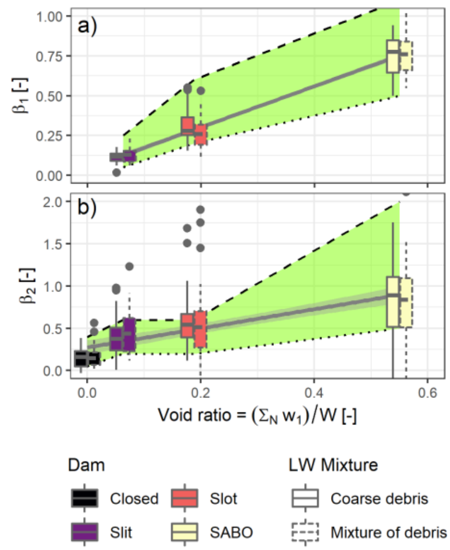

Figure 12. *Variability of β_1* and β_2 versus void ratio for all dams. Boxes display first, second and third quartiles, points are outliers higher than the 1.5 the interquartile range. Grey lines are linear fits on all data highlighting the increasing trends.The light grey ribbon and dotted lines show the upper and lower bounds fitted for each dam. Overall headloss coefficients increase with barrier permeability but presence of fine material or only of coarse debris has marginal influence

Two boxplots are displayed in Figure 12 for each dam. They are computed on data measured with and without pine needles figuring twigs and branches at real scale. According to the literature, higher relative head losses are expected on structures with high void ratio (e.g., rack dams) in presence of fine floating material (Schalko et al., 2018, 2019a), which is not observed here. The random variation of β_j between mixtures, repetitions, volume of LW and water discharge is higher than the eventual effect of fine material. It is also possible that our fine material was not fine enough to percolate through the accumulation as leaves and fine organic matter would. Schalko et al. (2018, 2019a) used plastic flexible elements to mimic leaves and demonstrated that the fine material content of the mixture was a significant parameter of the head loss computation. Predicting the amount of fine material that will percolate in a LW jam on a given site is however uncertain and thus equations using this parameter might be difficult to use. When accounting for energy head in hydraulic computation, Table 2 demonstrates that relative energy head losses do not vary that much. Our results show that for SABO dam, β_1 varies in the range 0.5-1.1. This range encompasses the values of $\Delta H/H_0$ measured by Schalko et al. (2019a) and thus the potential effect of fine material. Schmocker and Hager (2013) reported values of $\Delta H/H_0$ reaching 1.4, which may be used as an upper bound of β_1 along with the use of *H* in place of *h* (see Section 2 and Appendix A), if extremely high volumes of LW can be expected and would not overtop the dam.

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Using the results of this paper, it seems possible to bound the possible effect of LW reaching an open check dam. Only an estimation of the bounds~~ing~~ is possible because random variations in the arrangement and effects of LW ~~are incompressible~~cannot be reduced. Rather than trying to compute a most probable water depth, we thus recommend using upper and lower bounds as "pessimistic" and "optimistic" scenarios. It is worth being stressed that which of the upper or lower bound is the pessimistic scenario is a matter of perspective. For instance, the pessimistic (i.e., conservative) scenario for the design of the dam wings against overflowing is obviously the upper bound of β_i which will compute the highest head losses and flow level. Conversely, higher water level is associated with higher sediment trapping capacity (Piton and Recking, 2016a). Consequently, regarding the design criteria of sediment trapping capacity, the pessimistic scenario is the one with low water level, namely β_i lower bound (Bezzola et al., 2004). In essence, we recommend designers to consider two extremal scenarios rather than a mean behaviour, and to use each scenario, whenever it is the conservative option, as an assumption for further design steps.

Using this approach, it is possible to assess the discharge that might result in an overtopping of the structure. ~~In a~~A first step, the range of flow depth *h* possibly observed for a given discharge can be computed with Eq. (4) and the lower and upper bounds of β_1 and β_2 can be identified for the selected type of dam (using values from ~~Table 2~~ Table 2 or eventually an interpolation in ~~-~~Figure 12 with the Void Ratio). Assuming a range of *h*, it is possible to compute ranges of h^* and Π/F_D with Eqs. (5) and (9). If the flow is systematically in the floating carpet domain, LW releases are likely to occur either (i) in the range $3 < h^* < 5$ (if $1 < \Pi/FD < 10$) or (ii) in the range $1.5 < h^* < 3$ (if $\Pi/F_D > 10$). If conversely flows enter the piling jam domain, i.e., where $\Pi/F_D < 1$~~.0~~, it can be expected that LW releases occur for $h^* > 3$, up to $h^* \approx 10$ for $\Pi/F_D \approx 0.3$. Using the upper and lower bound of β_i will result in two values of h and thus several couples of h* and Π/F_D. Threshold values for overtopping can then be associated with several values of discharge. A typical conclusion would then be that, for instance "overtopping and release of LW might occur for discharge ranging from 40-60 m³/s, depending on the random arrangement of LW and of LW features (sizes, diameter, presence of key large pieces, all being also uncertain)".

For an overflowing structure or in openings, w~~W~~hen ~~structures~~ flow width of the structure is~~are~~ close to the length of LW, notably the key long elements ~~length or equipped with openings~~, it cannot be excluded that LW forms arches ~~or get entangled in openings and in the LW jam~~, thus resulting in more stable jams ~~*h** triggering releases, t~~. The narrower the structure and the more numerous the openings, the higher ~~the~~ h^* increases before release. It is known that for log length two to three times longer than the opening width, the trapping efficacy become very high and release becomes more unlikely (Piton and Recking, 2016b). For logs of length comprised in the range 1-3 times the flow width, it is partially stochastic (see Horiguchi et al., 2015, Rossi and Armanini, 2019, Meninno et al., 2019, Chen et al., 2020).

5.3 Other application of Π/F_D: Back analysis of numerical 1D and 2D models

Another possible use of our approach could be to identify where floating carpets or dense 3D jams might form using results of numerical models based on shallow water equations (~~thus,~~i.e. computing depth-averaged velocities). Diverse approaches to compute LW trajectories and effects were proposed (Addy and Wilkinson, 2019; Stockstill et al., 2009). The advanced way to fully describ~~eing~~ log trajectories is by coupling depth-averaged models with Lagrangian descriptions of ~~logs~~ logs. This currently relies on the hypothesis that the logs are floating (Ruiz-Villanueva et al., 2014a), i.e., on the hypothesis that flows stays in the floating carpet domain. It would be easy to create maps of Π/F_D based on numerical model results, which could help to identify where flows leave the floating carpet domain, i.e. areas where the model might underestimate LW jam packing and where ~~the result~~ interpretation of the results should be considered with more caution. The use~~Using~~ of 3D flow models makes possible to compute ~~more~~ in more detail LW behaviour but requires much more computational power (Kimura and Kitazono, 2019).

5.4 Limitations of the approach

5.4.1 Non-unique constant head loss~~es~~ coefficient

Trends of increases followed by decreases of β_i with discharge were highlighted in Figure 6~~Figure 6~~-9 and could be modelled with a statistical approach. The scattering related to the random variation between runs is, however, bigger than the variation with discharge for a given run. The approach proposed by this paper aimed~~ing~~ at being simple to use, therefore, constant values bounding ~~of~~ β_i were retained rather than β_i coefficients changing with Q or Π/F_D.

When the dam crest is overflowed, discharge $Q = Q_1 + Q_2$ and the head loss Δh is driven by ~~the fruit of~~ both β_1 and β_2. For a unique combination of water depth, $h=\Delta h+h_0$, and discharge, Q~~For a given couple ($h = \Delta h+h$, Q)~~, several possible combinations~~couples of values~~ of β_1~~,~~ and β_2 values may be considered (Figure 4~~Figure 4~~). There is ~~thus~~ a non-uniqueness of possible β_i parameters for each ~~couple~~water depth and discharge combo. ~~We~~ This is overcome ~~this non-uniqueness~~ by defining constant bounding values for the β_i parameters for ~~bounding~~ the whole range of discharge tested for each dam. A sensitivity analysis using other β_i coefficients is provided in supplemental material to demonstrate that using lower or higher values of β_1 or β_2 will not be relevant over the same full range of discharges~~does not allow describing each entire sample~~ to bound the measured water depth.

5.4.2 Uncertain buoyancy to drag force ratio

It is worth ~~being~~ stress~~ed~~ing that the way buoyancy, drag force and thus the ratio Π/F_D are computed relies on several crude hypotheses presented above. Π/F_D is clearly not an accurate ratio capturing all the subtle effects of log shape, roughness and flow approaching conditions. Π/F_D also ignores the effect of other logs, antecedent flow conditions ~~or~~ and the complex flow 3D pattern in the vicinity of the dam and LW jam ~~vicinity~~. Π/F_D should merely be considered a proxy of the buoyancy to drag force ratio to identify in a ~~coarse~~ crude way whether LW might accumulate as a floating carpet or as ~~in~~ a dense 3D jam. Further experiments aiming at refining the threshold value of Π/F_D and its uncertainty are necessary. Other formulations, using more detailed expressions of drag force or buoyancy or other dimensionless~~s~~ numbers, could be relevant. For instance, Kimura and Kitazono (2019) ~~for instance~~ proposed the ~~o~~ use of ~~the~~ "driftwood Richardson number" DRI=($\cancel{\rho_s}\rho_{LW}-\rho$)/($\rho Fr^2$), which is the ratio between buoyancy and inertial force, to ~~discriminate~~ discriminate LW accumulating ~~against~~at bridge piles as floating carpet or as~~in~~ 3D jams. Π/F_D worked better than DRI on our data so we did not push further their concept, but they inspired us to define Π/F_D.

6 Conclusion

Debris basins equipped with open check dams are key structures in the mitigation of hazards due to solid transport (sediment and LW). Open check dams aim at trapping all or some of the~~part of~~ sediment and/or LW. They are compound structures with openings partway through the dam and with a safety spillway on ~~a~~top. These hydraulic structures are usually designed considering, on the one hand, ~~transported element~~boulder and log sizes and opening sizes to assess the clogging probability and, on the other hand, using hydraulic equations to estimate flow depth, overflowing height and basin filling. Although LW has prove~~d~~n to significantly ~~profoundly trouble~~ affect the proper~~open check dam~~ functioning of open check dams in the past, its accumulation is still often ignored in the design, notably due to the lack of comprehensive stud~~y~~ies on the effects of LW~~ effects~~ on open check dam hydraulics. In the worst cases, open check dams are overflowed at~~by~~ such a depth that the LW ~~are~~ is ~~finally~~ suddenly released, ~~eventually~~ triggering high damage aggravation downstream. The few works addressing LW releases have so far been~~were so far only~~ dedicated to reservoir dam spillways. No previous ~~works~~ studies have ~~No works~~ so far addressed in such details compound structures with both openings and an upper spillway as the present paper.

This paper presents a comprehensive analysis of the disturbance induced by LW ~~in~~ on open check dam hydraulics and of their release conditions. A framework of analysis using simple dimensionless coefficients was developed to compute the relative increase in water depth related to LW presence. ~~We~~ It was demonstrated that flow depth might increase by 5%-40% on weirs, by 20%-60% on slit and slot dams, and by 50% - 200% on racks and SABO dams. These results are consistent with data from the literature on dam reservoir spillways or on LW racks, and ~~thus~~ seem transferable to other similar structures.

In addition, it was highlighted that LW may be released over the structures for overflowing water depth higher than 3-5 times the LW-diameters. This value is higher than the range of 1.5 – 2 times the LW-diameters measured on dam reservoir spillways because LW tends to get ~~entangled~~ more tightly entangled ~~against~~at open check dams than in the tranquil lakes formed by reservoir dams. In order to anticipate whether the LW might accumulated as a single-layer floating carpet or as a dense 3D jam, a new dimensionless number was proposed. This ratio of buoyancy to drag force captures~~, without calibration,~~ the transition from the regime of floating carpets to the regime of dense multi-layer jams. T~~, t~~he latter is~~being~~ more stable, requires greater~~leased for higher~~ flow depths for LW releases~~but~~ but also trigger higher head losses.

Notation

C_D Drag coefficient of logs (-)

$D_{LW\,mean}$ Arithmetic mean log diameter (m)

F_D Drag force on logs (N)

Fr Froude number, with LW $Q/(gW^2h^3)^{0.5}$

Fr_0 Froude number, without LW $Q/(gW^2h_0^3)^{0.5}$

H Flow energy head, with LW, $h+Q^2/2gW^2h^2$ (m)

H_0 Flow energy head, without LW, $h_0+Q^2/2gW^2h_0^2$ (m)

h Flow depth upstream of the open check dam, with LW (m)

h_0 Flow depth upstream of the open check dam, without LW (m)

Δh LW-related head loss, h-h_0 (m)

ΔH LW-related energy head loss, H-H_0 (m)

$h*$ Dimensionless overtopping depth, $(h-z_2)/D_{LW,mean}$ (-)

g Gravitational acceleration (9.81 m/s²)

$L_{LW\,mean}$ Arithmetic mean log length (m)

N Number of slit or orifices (-)

Q Total water discharge (m³/s)

Q_1 Water discharge passing through the dam (m³/s)

Q_2 Water discharge passing over the dam (m³/s)

V Section averaged flow velocity, $Q/(Wh)$ (m/s)

v Flow velocity near logs (m.s)

V_s Solid LW volume, V_S (m³)

$V_{s,rel}$ Dimensionless relative solid LW volume, $V_S/(Wh_0^2)$ (-)

W Flume width (m)

W_1 Orifice or slit width (m)

W_2 Crest horizontal width (m)

z_2 Dam crest level (m)

β_1 Dimensionless head loss coefficient for flow passing through the dam (-)

β_2 Dimensionless head loss coefficient for flow passing over the dam (-)

Φ Angle between horizontal and wing crest (°)

Π Buoyancy force (N)

ρ Water density (kg/m³)

ρ_{LW} Large wood density (kg/m³)

μ_1 Orifice coefficient (-)

μ_2 Weir coefficient (-)

Appendix A

~~Relative energy loss~~Relative energy head loss is computed using:

$$\frac{\Delta H}{H_0}=\frac{H-H_0}{H_0}=\frac{H}{H_0}-1=\frac{h\left(1+\frac{Q^2}{2\mathrm{gh}^3W^2}\right)}{h_0\left(1+\frac{Q^2}{2\mathrm{gh}_0^3W^2}\right)}-1=\frac{(h_0+\Delta h)\left(1+\frac{Q^2}{2gW^2(h_0+\Delta h)^3}\right)}{h_0\left(1+\frac{Fr_0^2}{2}\right)}-1=$$

$$\frac{\left(1+\frac{\Delta h}{h_0}\right)\left(1+\frac{Q^2}{2gW^2h_0^3}\frac{h_0^3}{(h_0+\Delta h)^3}\right)}{\left(1+\frac{Fr_0^2}{2}\right)}-1=\frac{\left(1+\frac{\Delta h}{h_0}\right)\left(1+\frac{Fr_0^2}{2}\frac{1}{\left(1+\frac{\Delta h}{h_0}\right)^3}\right)}{\left(1+\frac{Fr_0^2}{2}\right)}-1 \qquad \text{(A1)}$$

In the domain Fr_0 <0.3, $1.05>\left(1+\frac{Fr_0^2}{2}\right)\approx 1$ and $1.05>\left(1+\frac{Fr_0^2}{2}\frac{1}{\left(1+\frac{\Delta h}{h_0}\right)^3}\right)\approx 1$ thus Eq. (A1) can be simplified in $\frac{\Delta H}{H_0}\approx\frac{\Delta h}{h_0}$.

Conversely for $Fr_0 > 0.3$, Eq. (A1) should be used because $\frac{\Delta H}{H_0}\approx\frac{\Delta h}{h_0}$ become quite inaccurate.

Data availability

All data used in this paper are provided in the supplemental data. M~~and moo~~re pictures are available in the technical report Piton et al. (2019b) from: https://hal.archives-ouvertes.fr/hal-02515247. This report in French, which has not been peer-reviewed, was delivered to the French Ministry of Environement which funded this study.

Author contribution

GP lead the study, performed the analysis and wrote the paper, TH and LS performed the experiments, contributed to the analysis and reviewed the paper, SL supervised the study and reviewed the paper.

Competing interests

The authors declare that they have no conflict of interest.

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