Response to the reviewer:

We are thankful and appreciative for the constructive comments and feedback that have helped us improve the overall quality and clarity of the manuscript. Specifically, dealing with the reasons behind the different morphological responses of mountain river confluences vs. lowland confluences. We have included a response to the reviewers' main comments/conclusions below, the line-by-line comments are addressed here, have been implemented, and will be reflected in the re-submitted manuscript one the discussion period has ended. Our response is the blue text.

Summary

The manuscript presents findings from laboratory studies on confluences in mountain streams. It builds upon a recently published work by St. Pierre Ostrander et al. (2023). In this paper, the experimental program has been extended by 30 additional tests to focus on the effect of the tributary gradient and confluence angle. The experiments were conducted for different total discharges, sediment concentration, tributary gradient, and confluence angle. The model values were based on information of more than 100 confluences in Italy and Austria. The results demonstrate that the discharge and sediment concentration affect the morphology of the confluence. In contrast, tributary gradient and confluence angle had only a minor effect. For all tests, similar morphological features have been observed, including deposition cone, separation zone bar, or scour.

Main comments / Conclusion

The paper is well written and the differences or extensions compare to St. Pierre Ostrander et al. (2023) are clear. The experiments have been conducted thoroughly and the findings are presented in a comprehensive way. I have the following main comments:

1. Main outcome of the paper is that the confluence angle does not affect confluence morphology, which is different compared to low-land rivers. Please add to Introduction and Conclusions what the findings of the low-land rivers literature were with respect to the confluence angle and describe the physics behind it. Why is this different for mountain streams?

   Response: We agree with the reviewer's comment that detail was lacking regarding the confluence angle, we have added details which has improved the clarity of the manuscript. In lowland regions increasing both the discharge ratio and the confluence angle leads to a greater mutual deflection of flows and a larger separation zone which is the largest sink for tributary transported sediment (Best, 1987). Flow deflection influences the shear layers generated between the two converging flows along which powerful vortices are created and are responsible for increased bed shear stresses (Mosley, 1976; Best, 1987; Penna et al., 2018; De Serres et al., 1999). Decreasing the confluence angle results in a greater mixing of flows, a smaller separation zone, and declined levels of turbulence in the junction (Best, 1988; Penna et al., 2018). The most apparent differences result from the elevated intensity of hydraulic and hydrologic processes occurring in steep mountain channels (Rickenmann, 2016) relative to the much less intense conditions found in lowland channels. This is apparent considering the smaller Froude numbers and velocities measured in studies dealing with lowland confluences (e.g., Best, 1988; Biron et al., 1996), compared to the Froude numbers and velocities from our study and velocities from steep tributaries in the study region (e.g., Hübl et al., 2005). The higher Froude numbers and associated velocities not only intensify the event (Rudolf-Miklau et al., 2013) and the rate of channel adjustments (Wohl, 2010) but can also support equal mobility sediment transport conditions (Rickenmann, 2016) which can deliver massive amounts of sediment to the confluence, creating morphological feedback where the morphology reacts to the intensity of the event to maximize sediment transport capacity (White et al., 1982; Wohl, 2010). This explains why we observed the same general morphological patterns for different geometric configurations, given the same hydraulic parameters and sediment supply rates. Additional text and a table of hydraulic variables from the study have been added to the introduction (L69-85) and to the conclusion (L557-578) which was rewritten to better convey the key points as suggested by the reviewer.

Best, J. L.: Sediment transport and bed morphology at river channel confluences, Sedimentology, 35, 481-498, doi:10.1111/j.1365-3091.1988.tb00999.x, 1988.

Biron, P., Roy, A. G., & Best, J. L.: Turbulent flow structure at Concordant and discordant open-channel confluences. Exp Fluids, 21(6), 437–446, doi:10.1007/bf00189046, 1996.

De Serres, B., Roy, A., Biron, P., and Best, J. L.: Three-dimensional flow structure at a river channel confluence with discordant beds, Geomorphology, 26, 313-335, doi:10.1016/S0169-555X(98)00064-6, 1999.

Hübl, J., Ganahl, E., Bacher, M., Chiari, M., Holub, M., Kaitna, R., Prokop, A., Dunwoody, G., Forster, A., Schneiderbauer, S.: Dokumentation der Wildbachereignisse vom 22./23. August 2005 in Tirol, Band 1: Generelle Aufnahme (5W-Standard); IAN Report 109 Band 1, Institut für Alpine Naturgefahren, Universität für Bodenkultur-Wien (unveröffentlicht), 2005.

Mosley, M. P.: An experimental study of channel confluences, J. Geol., 84(5), 535-562, doi:10.1086/628230, 1976

Penna, N.; De Marchis, M.: Canelas, O.B.; Napoli, E.; Cardoso, A.H.; Gaudio, R.: Effect of the Junction Angle on Turbulent Flow at a Hydraulic Confluence. Water, 10, 469, doi:10.3390/w10040469, 2018.

Rickenmann, D. (Ed.).: Methods for the Quantitative Assessment of Channel Processes in Torrents (Steep Streams). CRC Press, 2016.

Rudolf-Miklau, F., Suda, J. Design Criteria for Torrential Barriers. In: Schneuwly-Bollschweiler, M., Stoffel, M., Rudolf-Miklau, F. (eds) Dating Torrential Processes on Fans and Cones. Adv. Glob. Change Res., vol 47. Springer, Dordrecht, doi:10.1007/978-94-007-4336-6_26, 2013.

White, W. R., R. Bettess, and E. Paris: Analytical approach to river regime, J. Hydraul. Div. Am. Soc. Civ. Eng., 108, 1179– 1193, doi:10.1061/JYCEAJ.0005914, 1982.

Wohl, E. E..: Mountain rivers revisited. American Geophysical Union/Geopress ISBN 9780875903231, 2010.

2. The focus of this paper was on confluence angle and tributary gradient: why did the paper include only 2 different angles and 2 different gradients, while 5 total discharges and 3 different sediment concentrations (per discharge) were tested? In addition, why did you decide to not vary the discharge ratio, as this was also mentioned in the outlook of St. Pierre Ostrander et al. (2023)?

   Response: The choice of geometric adjustments was based on the most occurring values in the study region for the confluence angle and tributary gradient. The reason why our study is limited to the presented channel configurations is the time, financial commitment, and project duration required to make additional changes. The discharge ratio was fixed, although adjustments were mentioned in the outlook of St. Pierre Ostrander et al. (2023), so that we could have fully comparable sets of experiments where any morphological response is from the changes in hydraulics and sediment transport from geometric changes. If limiting factors were not an issue, an ideal experiment plan would have the same 45 experiments run again, but with a different discharge ratio. However, Holzner et al. (2024) used the first 15 experiments from this study to validate a 2D numerical model (BASEMENT). With the validated model they test the effects of doubling the discharge ratio using an upscaled (30) version of the physical model used in this study.

   The discharges represent flood conditions and one extreme event in the study region, and varying sediment supply rates have been introduced in some of the first studies dealing with confluence morphology (Mosley, 1976). Testing these discharges allowed us to determine if certain morphologies correspond to certain RI events, while the 3 sediment concentration groups enabled an assessment of morphologies as they relate to different sediment concentration events where varying levels of transport capacity utilization may affect confluence morphodynamics.

Holzner, J., Ostrander, T. St., Andreoli, A., Mazzorana, B., Comiti, F., & Gems, B.: 2D numerical modeling of intense bedload-transport processes at confluences of Mountain Rivers and steep tributaries. Nat Hazards. doi:10.1007/s11069-023-06212-6, 2024.

Mosley, M. P.: An experimental study of channel confluences, J. Geol., 84(5), 535-562, doi:10.1086/628230, 1976

St. Pierre Ostrander, T., Holzner, J., Mazzorana, B., Gorfer, M., Andreoli, A., Comiti, F., and Gems, B.: Confluence morphodynamics in Mountain Rivers in response to intense tributary bedload input, Earth Surf. Processes, 1-22, doi:10.1002/esp.5613, 2023.

3. How was “equilibrium” defined? Was it achieved after the 20 minutes of test run and did it not take longer? See for example Ancey (2020a,b): https://doi.org/10.1080/00221686.2019.1702594 and https://www.tandfonline.com/doi/full/10.1080/00221686.2019.1702595

Response: The 2 provided references (which have been added to the text L105-108) certainly show the complications and factors which make predicting bedload transport difficult and the multitude of approaches (Ancey, 2020a), developed over the last decades to evaluate and predict bedload transport and the resulting bedforms. In this context, we understand the need to discuss how tending towards equilibrium morphology was defined. Ancey (2020b) asks a similar question in defining bed equilibrium, where researchers have stated equilibrium is met when fluctuations are slow. However, Ancey (2020b) points out that the problem of fluctuating bed load transport is rarely mentioned, which as Ancey (2020b) suggests, could be at the very core of understanding and developing more accurate approaches to predicting bed load transport. In this regard, we ensured that we described the resulting morphology as one that is tending towards an equilibrium state that is representative of the driving impact factors which is optimized to deal with the intense nature of the event.

The tending towards equilibrium morphology was defined by the stable, large-scale, reoccurring, geomorphic units which reoccurred for every experiment with identical input conditions. From video registrations and direct observations, we were able to establish that the final morphology is reached after a relatively short duration and remains stable throughout the experiment. This morphology is event-specific and can certainly be altered by changes in event characteristics, for example, discussed in Ancey (2020a) the mixing of fast and slow processes (amongst others). Additionally, Ancey (2020b) discusses how rivers are closer to punctuated equilibrium systems, with rapid changes in bed morphology over short time intervals, then followed by long periods of stasis. The tending towards equilibrium morphology discussed in the presented work represents these punctuated moments of intensity, that would certainly be re-worked during prolonged periods of weak activity. Being that the presented work deals exclusively with torrential hazard events the speed of the processes was consistently fast (Wohl, 2010) as such the large-scale morphology, adapted to the intensity of the event remained stable once established.

Furthermore, Holzner et al. (2024) used the results from the physical model, used in this study (EXP 1-15), to validate a 2D morphological numerical model (BASEMENT). To ensure that the resulting morphology did indeed represent a system tending towards morphological equilibrium the 2D numerical model was run for a duration of 54h, which corresponds to a 10h experimental run, which is far longer than a typical torrential hazard event. The results confirmed that the morphology captured at the end of a physical experiment was indeed a stable system tending towards equilibrium. The reason for morphological equilibrium to be established in a short relative time frame deals with the intensity of modelling torrential events. Processes occur much faster because of the gradient of the tributary channel and high sediment loads and discharges (See response to comment 1).

Ancey, C.: Bedload transport: A walk between randomness and determinism. part 1. the state of the art. J. Hydraul. Res., 58(1), 1–17. doi:10.1080/00221686.2019.1702594, 2020a

Ancey, C.: Bedload transport: A walk between randomness and determinism. part 2. challenges and prospects. J. Hydraul. Res., *58*(1), 18–33. doi:10.1080/00221686.2019.1702595, 2020b

Wohl, E. E..: Mountain rivers revisited. American Geophysical Union/Geopress, Washington, D.C., ISBN 9780875903231, 2010.

Holzner, J., Ostrander, T. St., Andreoli, A., Mazzorana, B., Comiti, F., & Gems, B.: 2D numerical modeling of intense bedload-transport processes at confluences of Mountain Rivers and steep tributaries. Nat Hazards. doi:10.1007/s11069-023-06212-6, 2024.

I provide additional comments per line below. Based on my review, I recommend minor revision in form and content.

Comments per section/line

Response: All revisions that have been suggested by the reviewer have been implemented. Line numbers reflect the current version of the revised manuscript but will certainly change as we continue to revise based on further comments and suggestions.

1. L116: Please add why these hypotheses have been formulated; what potential processes or governing parameters lead to these hypotheses?

   Response: Details into the formulation of the hypotheses have been added (L141-146) and primarily deal with the conclusions drawn from Lane (1955), St. Pierre Ostrander et al. (2023), and White et al. (1982). St Pierre Ostrander et al. (2023) established additional factors besides the confluence angle and discharge ratio influence confluence morphology (hypothesis 1), and Lane (1955) and White et al. (1982) describe how a channel will react to the impact conditions to establish an event based morphological equilibrium (hypothesis 2) to maximize or minimize the value of a specific parameter, like sediment transport, for example.

2. L151: see also main comment 2, but why 5 discharges and why steady-state?

   Response: The 5 discharges represent flood conditions and one extreme event. This allowed us to determine if morphological patterns correspond to certain reoccurrence intervals while also thoroughly representing the hydraulic conditions in the study region. Steady-state modelling was used so that morphological development could more easily be associated with one of the introduced factors and to make the morphological development comparable to research dealing with lowland confluences, which largely assume steady-state conditions. An unsteady hydrograph would make it difficult to discern at what point (rising limb etc.) the morphology reacts to the impact factors and to which one. Steady-state modelling mitigates this uncertainty and in this application is consistent with other modelling approaches regarding the hydrodynamics and morphological development of mountain river confluences (e.g., Roca et al., 2009; Leite Ribeiro et al., 2012). Text has been added to clarify this component of the experimental plan (L177-184).

3. L155ff: Please add the accuracy of the measurement devices.

   Response: The accuracy of the measurement devices has been added to the text following the reviewer's suggestions (L187-189).

4. L162: Why 20 minutes? Which scaling factor did you choose and what was the reference value to derive this duration?

   Response: Scaling was done according to Froude similarity; transferring model dimensions to nature allows a scale factor range of 20-40. The scale is determined by the width of the tributary at the confluence relative to the width of the tributary in the physical model and was referred to as the specific Event duration was scaled down to laboratory conditions by a factor of 30. Thirty was chosen as it is the median scale factor the physical model is designed to accommodate. The event duration is based on incident reports of torrential events occurring within the study region compiled by the Tyrol Torrent and Avalanche Control Agency (WLV) and other sources of event documentation, for example, Hübl et al. (2012). Text has been added to clarify this aspect L196-197.

5. Table 1: Not all parameters have been introduced in the text or in the table (e.g., Qm, Qt). Please check entire manuscript. Please add Froude number and stream power to the table.

   Response: Variable descriptions have been added to the table caption (L212-215). Unit stream power for all experiments is summarized in Table 4, and clear water hydraulic variables are added to Table 1 (L82). The main channel was modified with a fixed bed for all geometric configurations to obtain these values since direct flow field measurements were not possible during an experiment. The values in Table 1 represent the undisturbed, initial conditions at the onset of an experiment and are indicators of the initial hydraulic conditions which initiate the depositional or erosional patterns in the confluence.

6. Equation 1: please introduce right after you first mention it and also introduce the parameter.

   Response: The equation has been moved to immediately follow its introduction (L256).

7. L244: “Discharges and related unit stream power above 45 l s-1” … please add unit stream power or write 45 l/s after discharge, otherwise confusing.

   Response: The text has been revised to reflect the reviewers’ comment (L281).

8. L249: Reference to subcritical flows – would be interesting to know Froude numbers of this study (see recommendation for Table 1)

   Response: Froude numbers have been added to Table 1.

9. Section 3.2+3.3.: Consider stating the value of the tributary gradient in addition to the test number; difficult to remember the test number that refers to a certain gradient. This would be especially helpful in the Figure captions and I recommend making them consistent.

   Response: Geometrical parameters and experiment numbers have been added to the text in both sections. We agree with the reviewer that additional details were required to impart greater clarity (L317-318, L320, L325, L330-331, L334, L337-338, L340-341).

10. L278: Here, I recommend to state the gradient value instead of "from the decrease in gradient". For example: "A smaller tributary gradient of 5% led to reduced velocity and … compared to the depositional forms with a tributary gradient of 10%" or similar.

    Response: The suggestion has been added to the text as we agree that clarification is needed when discussing the sets of experiments (L315-318).

11. Figure 4: figure caption "supporting a qualitative representation of morphological differences" is different to L279 that the gradient did not have an effect. I recommend deleting the sentence on the qualitative representation in the figure caption.

    Response: The sentence has been deleted according to suggestion (L325).

12. L295: add gradients and add test numbers in brackets + refer to Table 1

Response: Geometrical parameters and experiment numbers have been added in brackets and hydraulic variables have been compiled in Table 1 which has been referenced in the text (L329-337).

13. Figure 5: please add test number.

    Response: Experiment numbers have been added to impart greater clarity as suggested (L341-342).

14. Figure 6: please add tributary gradient

    Response: The tributary gradients have been added as suggested (L358-359).

15. L329: I recommend deleting the sentence on the qualitative representation in the figure caption.

    Response: The sentence has been deleted (L370-371).

16. Figure 8: please add test number.

    Response: The experiment numbers have been added to the caption to further clarify the figure (L382-384).

17. L349: Where are the results of the depositional volume plotted? Please add.

    Response: A reference to the figure has been added to the text (L391).

18. L356: Please revise this sentence; the statement is not clear to me. Consider adding the values of the confluence angle for clarification instead of “greater” – to what?

    Response: The value for the confluence angle has been added in place of “greater” (L397).

19. Figure 9: add angle to the caption

    Response: The corresponding gradients have been added to the caption to add clarity (L400-401).

20. Table 5+6: add sigma also to the last 3 columns

    Response: The sigma denotes the standard deviation, and the last three columns are the results of the pairwise post hoc mean comparison testing which uses letters to represent differences in means. The table caption required clarification to convey this and has been revised (L424-425, L456-458).

21. Figure 10: add reference to Table 4

    Response: A reference has been added to further clarify the figure (L438) and has also been added to the following boxplot figures to maintain consistency (Figure 11, L467 and Figure 12, L489).

22. L434: Add more details on why turbulence increasing with increasing confluence angle.

    Response: Additional details have been added to the text explaining the mechanisms behind the increased turbulence in the junction (L474-476).

23. Table 7: Why was a different statistical test used compared to the other factors? T-Test for angle compared to ANOVA for discharge and sediment concentration?

    Response: The confluence angle has 2 groups, 45° and 90°, the sediment concentration 3 groups, 5%, 7.5% and 10%, while the combined discharge has 5 groups, 16.5 l/s, 49.5 l/s, 82.5 l/s, 115.5 l/s, and 148.5 l/s The number of groups (and their distribution, and variance) determined the applied tests (Figure 2). A T-test requires 2 groups while ANOVA testing requires 3 groups. Text has been added to the caption of Fig. 2 to add clarity to this component (L246-247).

Sawyer, S. F.: Analysis of variance: The Fundamental Concepts. Journal of Manual & Manipulative Therapy, 17(2). doi:10.1179/jmt.2009.17.2.27e, 2009b

Witte, R. S., & Witte, J. S.: Statistics 11th Edition. Wiley and Sons, Hoboken, New Jersey ISBN 1119386055, 2017.

24. L452: See main comment 1. Please add references and briefly summarize physics behind it so the reader understands the differences between lowland and mountain streams.

Response: Additional details and references (below) have been added to the discussion section to further describe the factors and conditions that influence mountain river confluences and how they differ from lowland conditions (L494-508). We discuss how the confluence adjusts to the intensity of flooding and associated bed load transport occurring in steep channels and how this intensity does not occur in lowland channels, causing a different morphological response.

Darby, S. E., and M. J. Van De Wiel: Models in fluvial geomorphology, in Tools in Fluvial Geomorphology, edited by G. M. Kondolf and H. Piégay, pp. 503–537, John Wiley, Chichester, U.K., doi:10.1002/9781118648551.ch17, 2003.

Davies, T. R. H., and A. J. Sutherland: Extremal hypotheses for river behaviour, Water Resour. Res., 19, 141– 148, doi:10.1029/WR019i001p00141, 1983.

Liu, T., Fan, B., and Lu, J.: Sediment-flow interactions at channel confluences: A flume study, Adv. Mech. Eng., 7(6), 1-9, doi:10.1177/1687814015590525, 2015.

White, W. R., R. Bettess, and E. Paris: Analytical approach to river regime, J. Hydraul. Div. Am. Soc. Civ. Eng., 108, 1179– 1193, doi:10.1061/JYCEAJ.0005914, 1982.

Yang, C. T.: Minimum unit stream power and fluvial hydraulics, J. Hydraul. Div. Am. Soc. Civ. Eng., 102, 919– 934, doi:10.1061/JYCEAJ.0004589, 1976.

Yang, C. T., and C. C. S. Song: Theory of minimum rate of energy dissipation, J. Hydraul. Div. Am. Soc. Civ. Eng., 105, 769–784, doi:10.1029/WR017i004p01014, 1979.

25. L453: I recommend to remind the reader of hypothesis 1 and explain why it was confirmed. References to main plots in paper would be helpful.

    Response: Hypothesis 1 has been reiterated and figure references to plots and tables have been added to the text (L494-495).

26. L456: sympathetically? Not clear

    Response: Sympathetically has been removed to impart greater clarity (L511).

27. L472: I recommend to remind the reader of hypothesis 2 and again explain why the same geomorphic units occurred.

    Response: The hypothesis has been restated and an explanation for the reoccurrence of geomorphic units has been added to the text (L526-532).

28. Conclusions: see main comment 1 and consider rewriting the conclusion to add an explanation why the angle does not have an effect in mountain streams compared to lowland rivers. Last sentence comes a bit as a surprise and not so clear what is meant by sediment buffer zones.

    Response: We agree with the reviewer that the conclusion required further revisions. Accordingly, the conclusion has been re-written (L565-586) with details as to why confluence angle effects are limited in the presented work.