

Interactive comment on “Structure and evolution of the drainage system of a Himalayan debris-covered glacier, and its relationship with patterns of mass loss” by Douglas I. Benn et al.

D.J. Quincey (Referee)

d.j.quincey@leeds.ac.uk

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This paper brings together a range of observations, some of which have been previously published, in an attempt to describe the complete hydrological system of the Ngozumpa Glacier in Nepal. It formalises some existing ideas as well as proposing some new ones, which other people working in this region will be able to test and build on in their own work. Some of the interpretation is slightly speculative, and given the same datasets it may be that others would arrive at different conclusions, but this should not detract from the value of assembling them in a single analysis and effectively joining the dots between them, for the first time on a glacier such as this. It is very well-written and the figures are high-quality. It should definitely be published in my

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view, but before it is there are a few gaps that could be closed up to make it an even stronger addition to the literature. These are detailed below, followed by some more minor comments and suggestions.

1. Part of the justification for the study (lines 63-71) is that we still know relatively little about englacial conduit formation, and specifically the relative importance of the three processes previously described in the two Gulley et al., 2009 papers and summarised in Benn et al., 2012. Although not stated explicitly, the subsequent analysis here suggests that cut-and-closure is the dominant, or even exclusive, mechanism, at least on Ngozumpa. Given that the argument against NG-01 to NG-03 being structurally controlled (lines 308-311) could be invoked for most conduits running parallel to flow, and that to my knowledge there have been no direct observations of hydrofracture here or in the wider region, some actual discussion of their relative importance would be an interesting addition to the manuscript. Based on their additional analysis, do the authors now believe that cut-and-closure is the dominant mechanism for these debris-covered glaciers, or does it just happen to prevail at Ngozumpa? Or is it paired, in that cut-and-closure forms the conduit in the first place, and then the relict channels provide the dominant structural control thereafter? Or some combination of these? Some clarification in the revised text would be a good addition.

2. The least-well constrained element of the paper is the analysis of the existence or otherwise of a subglacial hydrology, understandably so. In the absence of any direct observations, the velocity proxy provides some evidence for subglacial water in the upper ablation area, but if the authors are correct in their interpretation of this, what happens to it then? I'd be interested to see some further discussion of the lower ablation area – if as stated (line 507) all of the water leaving the glacier passes through Spillway Lake, do the authors propose that the subglacial waters from the upper ablation area pass through the lower ablation area and are then elevated at the terminus under pressure? Some direct measurement of the discharge would give an indication of whether it is at least the correct order of magnitude for a glacier of this size, but in

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the absence of this some discussion of whether it might go to deep groundwater, or shallow groundwater and then emerge further down-glacier, would fill this gap. The hollow that drains the supraglacial channels (line 384) is also important in this regard – it hints at a direct surface-to-bed connection but there is no further information given – can any more light be shed on where these waters go?

3. The interpretation that hummocky closed basins cannot support a supraglacial hydrology is believable, but there is a spatial mismatch between the analysis shown in Figure 9 and the observations shown in Figure 8, which detracts from the argument. If this is the dominant control on supraglacial water (and the interpretation in Figure 13 hangs on it being so) then can the analysis in Figure 8 be extended up so we can see if it prevails in the upper ablation area too? Or at least see some morphological/topographic differences between c) and d) in Figure 8?

Minor comments

L86: 7922 m here but 7952 m in Figure 1.

L95: I suggest stating that it is ‘effectively’ stagnant, since it is probably deforming at some rate, just not detectable by the satellite analysis.

L130 and elsewhere: just a note that the terms pond and lake are used interchangeably – I’d have a preference for using the former for the majority, which are perched and relatively small, and saving the latter for Spillway Lake, which is not.

L158-167: can you add some more detail on the masking/filtering that is evident in Figure 7? And what is the threshold of ‘detectable flow’ referred to in line 95 – I guess that should be mentioned here too.

L331: this is 7 km earlier in the manuscript.

L351: should these artifacts not be masked as per Fig 7a? As it stands, it looks like you have greater confidence in the speed-up data than the annual pair measurements, which can’t be right since you derive the former from the latter.

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L364-366: there's some contradiction with the Figure caption here – the text says there are only crevasses in the upper part of the clean ice tongue (c), but the caption states they are only in (a)?

L371-373: this is the only hint at what happens to the subglacial water after it descends from the upper ablation area – can you offer any insight into where it may go then?

L382-385: this hollow is quite an important part of the picture, particularly if it shows the surface is connected to the bed directly – is it the same hollow that Horodyskuj monitored? Is it a moulin? Can you offer any further information on it?

L396: Figure 9 does not extend sufficiently far up-glacier for us to be able to verify this is true – can you extend the analysis to make this argument more robust?

L402-415: the number of basins etc is interesting here but the upper boundary of the analysis seems arbitrarily defined. Why not cover the whole of the debris-covered area? That way others can repeat the analysis for future time periods and quantify the change.

L410: Figure 9 doesn't show any full drainage events, unless these are lumped into the < 1000 m² category? Shouldn't they be shown as 'empty'?

L425: do they have to be relict, necessarily?

L425-427: as above, I can't see the evidence for 35 drainage events – can you make this a bit clearer?

L424-427: can you add an acknowledgement that there is a seasonal signal in these data?

L439: they're probably underlain by thick sediment too, inhibiting bottom melt.

L456: this disparity between the number of basins on the west and the east sides merits some further comment – does it reflect the dominant englacial drainage pathway? Or debris-thickness? It's a stark contrast when looking at Figure 9.

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L460: missing 'the'

L471: Horodyskuj (2015) is not in the reference list.

L507: can you be sure that all of the water passes through Spillway Lake?

L518-521: can you bring this into line with the six elements stated in the abstract? Or vice versa?

L528: have you derived this 3° threshold value earlier on? I can't find it in the previous analysis or discussion – can you qualify it somehow?

L543-544: it'd be better to show these basins superimposed on Fig 14b, rather than repeating the channels on both figure panels.

L545: can you indicate where these elongate ponds are on the figure for clarity?

L546-549: the figure referred to here doesn't relate to the text. Do you mean figure 10 instead?

L553: where does this thickening debris cover come from?

L557: note cut-and-closure is hyphenated in some places but not in others.

L589: section numbering jumps one here.

L626-627: remove the bracketed text since it is clear already?

L662-664: interesting that the Khumbu ponds also follow what might be a sub-marginal channel.

L666: this sentence implies that Ngozumpa is in a more advanced stage of recession than others in the region – is this what you mean? I'm not sure it is much different to others except for Spillway Lake?

L669: maybe 'interpretation' is better than 'view' here?

Figure 7: mentioned above too, but how can b) have more coverage than a) given that

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it is derived from a)?

Figure 8: what are the coloured dashes here?

Figure 11: are there no better data than these TM images? Only because they're poor resolution. Do the 2010 and 2012 data you have not cover these areas? At least could you superimpose your interpreted pond boundaries?

Figure 12: maybe add that the reader should see the text for explanation of the annotations?

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