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Dear Editors,

Find below our response to reviewer comments and suggestions. In addressing them we have made significant revisions to our original manuscript and also invited participation of two new co-authors (Dirk van As and Samiah Moustafa). As detailed below, this revised manuscript now addresses the reviewers' concerns about data uncertainty. For example, in the original manuscript we presented one realization of ice sheet meltwater runoff and release to rivers. In the revised manuscript, however, we show that sparse basal topography data availability can lead to significant uncertainty in ice sheet catchment delineations. Therefore, rather than limiting our analysis one 'best' catchment, we now present three possible catchment delineations so as to quantify the range of uncertainty introduced through different use of surface and basal topography datasets.

After performing these additional analyses our conclusions remain similar to those of the original manuscript, namely that ice sheet meltwater retention and delayed release to the proglacial zone are possible. However, unlike the original manuscript we also discuss the possibility of changing effective catchment area, and also show that it is possible to "close" the ice sheet water balance through assumptions of very conservative winter discharge estimates for one of the three possible ice sheet catchment delineations. This "closure" scenario is such that it represents an extreme lower bound that is unlikely to take place. Thus, we show that meltwater retention and delayed release is likely to occur.

To our knowledge, this is the first study where such uncertainties have been considered, so we are grateful for the reviewers' comments and feel the manuscript has been substantially improved as a direct result of their feedback.

Yours Sincerely,

Dr. Asa Rennermalm

Response to review comments (comments by reviewers are in italics, emphasis is made by authors)

Response to comment by M. Pelto

1. *The high values of meltwater retained for 2010 and 2011* ***do not seem realistic*** *given previous work on the adjacent Kangerlussuaq catchment, and asks for more* ***attention to the specific energy balance and water balance of the watershed***
    1.1. The findings of the revised manuscript provides a more **thorough treatment of uncertainty in three key aspects**: 1) drainage area delineation is improved by also considering basal topography and providing three possible delineations (see detailed comments 1.4 and 1.4); 2) ice sheet runoff estimates are improved by including data from one additional ice sheet AWS station (see detailed comments in 4.1); 3) river discharge estimates are improved by adding more in situ observations to construct the rating curve, and by independent validation with data points measured with another technique slightly downstream (see detailed comments in 18.2).
    1.2. In the revised manuscript **we show that meltwater retention is likely even given the large uncertainties** with drainage area delineations because of 1) cumulative ice sheet and river discharge do not match in any year (see detailed comments in 1.6, 1.7, and 18.2; 2) time lags between meltwater production and release to the river. We furthermore show that the meltwater retention volume is small compared to the ice catchments' total ice volume, and **that it is plausible that this water can be stored in englacial and subglacial storages**. In the revised discussion we also consider the possibility that the effective drainage area may change from year to year. If this is true the subglacial retention hypothesis could potentially be false or retention less than predicted. Regardless, our results show convincingly that subglacial hydrology is highly variable from year to year, and that channel discharge varies from year to year. Furthermore, we show that meltwater can be released with a delay with several months.
    1.3. The previous work by Dirk van As and other published in The Cryosphere (Van As et al., 2012) showing good agreement between ice sheet runoff and river discharge in the Kangerlussuaq catchment was made at a much larger scale (~9600 km^2 compared to ~60km^2) and was compared with river discharge measured only from spring to fall. Thus, we believe that **scale and/or lack of winter observations may explain the differences** between our study and this study by Dirk van As. Furthermore, **van As study showed different runoff/discharge ratio's for the two year** in that study that was suggested to be attributed to catchment delineation errors. However, **it is possible that these two ratios are indicative of meltwater storage**. This is presented in the revised manuscript discussion
    1.4. A key revision was to include basal topography from the MCORDS ice thickness dataset provided by CReSIS at University of Kansas and NASA's Operation IceBridge to create a potentiometic surface from which the catchment was delineated. This method is considered better than relying

only on surface topography for catchment delineations (Cuffey & Paterson, 2010). However, we found many basal topography data points near the marginal area to be questionable (some data suggested zero or near zero ice sheet thickness, where thicker ice is present). Thus, we have created **three possible ice sheet drainage area delineations** based on three surfaces: 1) surface topographic data (W1, blue shape in **Figure 1**), 2) potentiometric surface determined with a sub sample of high density basal topographic data east of 49W (<49W, red dots in Figure 1) (W2, green shape in **Figure 1**), 3) potentiometric surface determined with all meaningful basal topographic data (red and yellow dots in Figure 2) (W3, orange shape in **Figure 1**).

1.5. It is difficult to determine which of these three watershed that are most realistic. Thus, we have revised the manuscript using all three delineations therby providing a range of possibilities that modifies our orignal conclusions. When using the two larger watersheds (W1 and W2) results are similar as in the first manuscript (Figure 2a). However, when using the smaller watershed (W3) the results are different with a larger release in 2008, and no retention in 2009 and 2010 (Figure 2b).

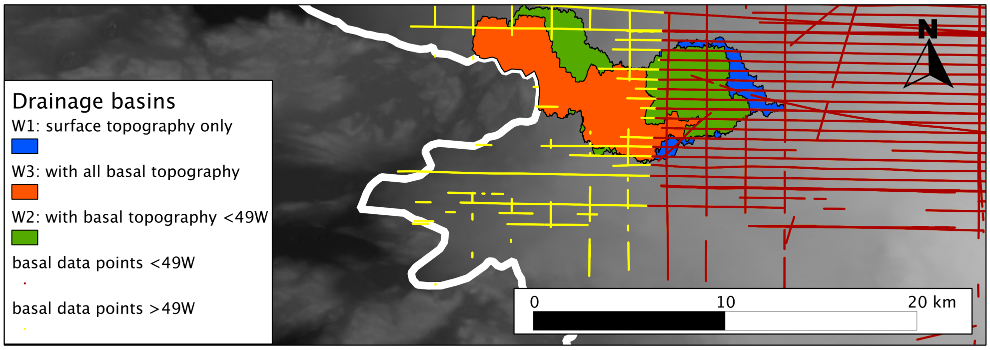

Figure 1. Three drainage area delineations using only surface topographic data (W1), using the potentiometric surface determined with basal topographic data <49W (W2), using all meaningful basal topographic data (W3). The ice sheet edge is outline in white overlain ASTER GDEM2 digital elevation data in gray shading. Note that the blue watershed (W1) is mostly covered by the green watershed (W2), and that the green watershed is mostly covered by the orange watershed (W3)

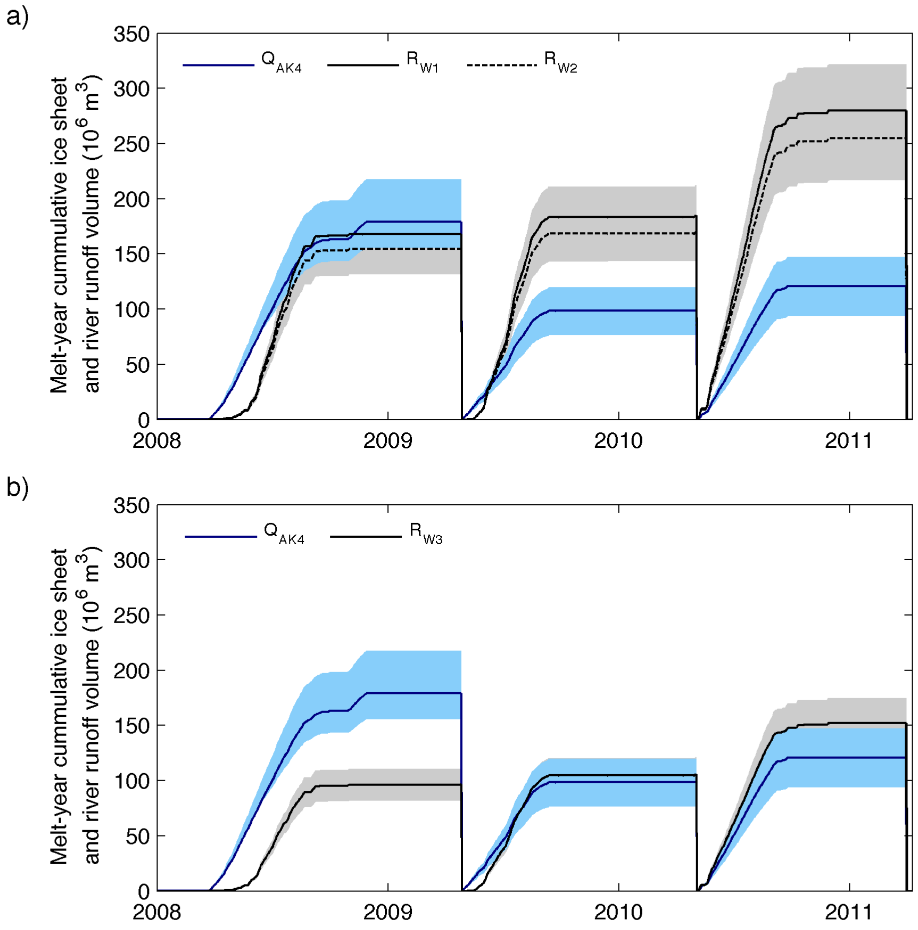

Figure 2. Melt-year cumulative ice sheet and river discharge volume in melt years 2008, 2009, and 2010. Top panel shows meltwater volume from ice sheet watershed W1 and W2; Bottom panel shows meltwater volume from ice sheet watershed W3. The melt year is defined from the river spring flow onset in two consecutive years.

1.6. None of the three watersheds meltwater retention/release is near water budget closure over three years (Figure 3). While W1 and W2 results in net retention, W3 results in net release.

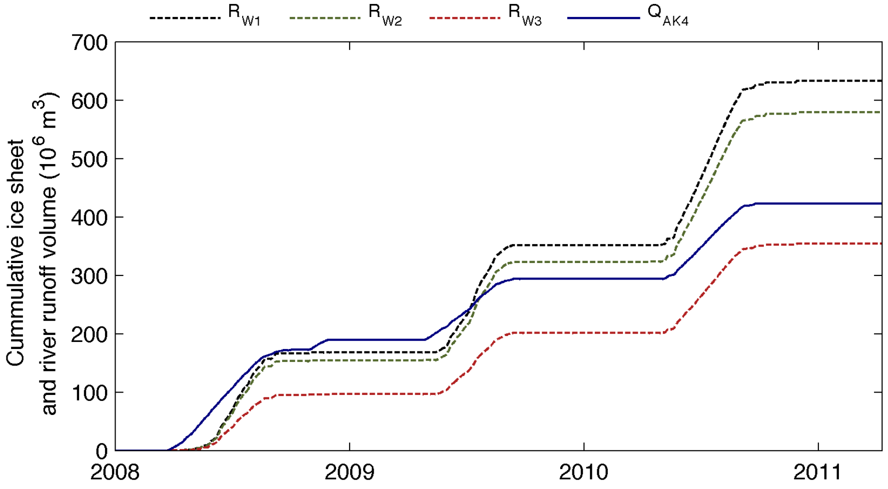

Figure 3. Cumulative ice sheet (R_{W1}, R_{W2}, and R_{W3}) and river discharge (Q_{AK4}) volume from 2008 to 2010.

1.7. Although the third watershed delineation (W3) results in less cumulative meltwater ice sheet runoff (Figure 3), time series data demonstrates evidence of delayed release in winter and spring. Only when a very conservative estimate of winter discharge is considered does the early spring and winter release become insignificant (see response to reviewer 3 in 18.2).

1.8. We have also adopted a runoff model that included one additional AWS station, which **better capture the true energy and water balance of the catchment.**

Response to Pelto's specific comments

2. *3371-15: Cite Brown et al (2011) meltwater retention amounts unique data set comparison.*

   2.1. The paper has been cited as requested.

3. *3373-27: Indicate the elevation of ELA close to 1500 m (van de Wal, et al, 2012).*

   3.1. The ELA position and reference to van de Wal has been added to the paper as requested.

4. *3374-23: Van den Broeke et al, (2011) observe that S5 is situated on the protruding tongue of Russell Glacier, and is influenced by the thermal characteristics of the surrounding ice-free tundra. The resultant enhanced turbulent heat exchange results in significant positive values for SHF and LHF.*

How has this energy enhancement been accommodated for *since your study area is not on a protruding tongue? Is the katabatic wind different than on the tongue of Russell Glacier for the study area?*

4.1. To improve the representation of the catchment melt conditions we have **included a third AWS station in the elevation dependent ice sheet runoff model.** This station is the KAN_L station operated by Geological Survey of Denmark and Greenland (GEUS). In fact, we replaced our original runoff model with a runoff model that has already been published (Van As et al., 2012) and is using the two K-transect station (S5, and S6) as well as the KAN_L station. Figure 4 shows that the geographical location of the KAN_L station is much closer to the three-catchment delineations and thus will **ensure more representative ice sheet runoff** for these catchments. **Any impact of enhanced turbulent fluxes on the glacier tongue are captured by the model.**

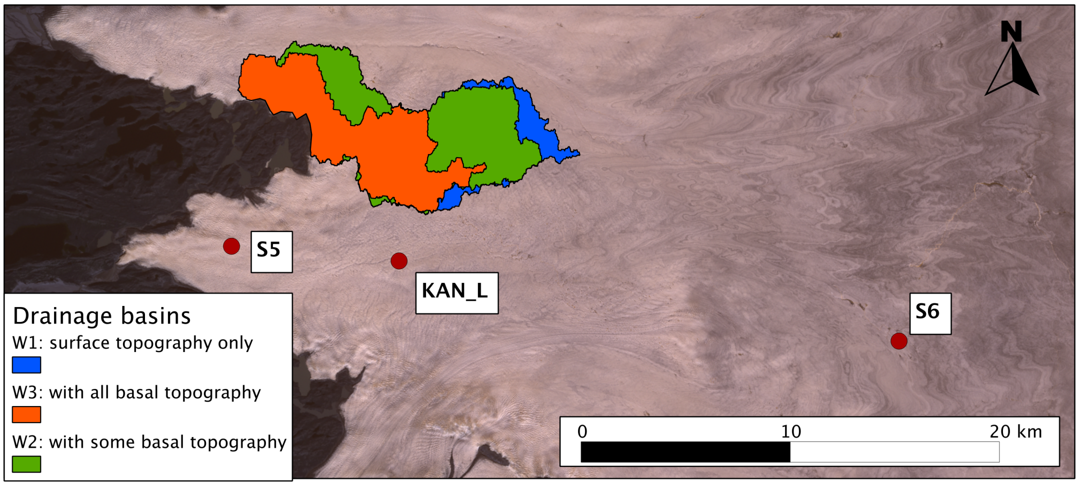

Figure 4. Position of the three AWS stations used in runoff modeling in relation to the three drainage areas delineations. The background image is a Landsat satellite images.

5. *3375-2: Given that the study area falls well below the local ELA of 1500 m any percolation and refreezing would be temporary.* ***Does the model distinguish the fact that refrozen meltwater in the seasonal snowpack is being melted for the second time, raising melt volume versus runoff volume?*** *The Gruell and Konzelmann (1994) model has meltwater runoff instantly when it reaches an ice surface. In the thin spring snowpack does meltwater in the model have to time to refreeze before reaching the ice surface****? If so how much is refrozen?*** *Van den Broeke et al (2008) indicate that at S6 23% of the total melt energy is consumed in snow melt and 40% refreezes in the snowpack temporarily. They further observe that refreezing is insignificant in the lower ablation zone, which S5 is considered to be in. What are the respective study area values? How is the remelting accounted for?*

5.1. **The model accounts for refreezing.** However, refreezing is **very small** due to very shallow snow cover in the ice sheet catchments. At each AWS station, snow depth sonic rangers are used to establish if ice or snow is present on the ground. If snow is present, meltwater percolate into the snow and refreeze given the presence of pore space and temperature deficit in a snow layer. If there is meltwater left after this, it moves down to the next layer and runoff if it reaches the ice sheet surface

6. *3375-5:* ***Why is S6 used since it is above the height of the study area and not SHR which at 710 m is well within the study area elevation range?*** *I understand SHR is a shorter duration site, but are the records for the study period just not continuous enough?*
    6.1. The **SHR site is also the location for the GEUS KAN_L weather station**, which has been measuring for 4.5 years. In the revised manuscript we have included data from the KAN_L AWS station near the catchments at 670 m a.s.l to improve the runoff model. **We argue that using AWS is advantageous over annual ablation stake records at SHR**, since the latter does not provide sufficient temporal resolution for this study.
7. *3376-19: Wrong seasonal wording in sentence.*
    7.1. Wording has been corrected as requested.
8. *3376-21: van de As et al (2012) note that in 2010 the runoff was more than twice as large for the Kangerlussuaq catchment than in 2009. This area has a much higher elevation range and the high elevation melt in 2010 could be the answer to this difference from the study area here.* ***It is important to include the actual melt volumes derived from each of the three seasons and the contrast to the Kangerlussuaq catchment is worth noting****. van de Wal, et al, (2012) provide annual balance gradients for the K-Transect,* ***how do the model results for your watershed compare?***
    8.1. See comment 1.3 regarding comparison with van de As' study. Furthermore, we argue that the reason why anomalously large melt was not observed in the W1, W2, W3 watersheds in 2010 (when it was observed for the larger Kangerlussuaq catchment) is due to **the fact that the entire catchment area will always be melting at these smaller watersheds** by the ice margin. In contrast, the melt area of the Kangerlussuaq catchment varies from year to year. This is discussed in the revised manuscript.
    8.2. The annual balance elevation gradient for the K-transect and our modeled runoff agree reasonably well. However, interannual variability using only 2008, 2009, and 2010 does not move in concert, but this may be due to only comparing three years. This comparison is shown in the revised manuscript.
9. *3379-7: Overall the authors do not* ***provide a convincing argument that the quite high values of retained meltwater found by the model are real and where they might be retained.*** *Sundal et al (2009) indicate that in this region lake supraglacial lake area and volume rises from near zero in early and falls to zero again by day early September. This is not a mechanism for retention in the watershed here. The watershed has a maximum elevation of 860 meters, well below the snowline of 1500 meters in the region. Retention of meltwater within snow or firnpack is not a potential mechanism beyond the short term spring storage, since the snow-firnpack is typically lost even at S6 by the end of June. The authors make an excellent case for the ease of the reactivation of the CHS which argues against subglacial storage, when a drainage network is easily activated by increased water input. Hence, only englacial storage remains as a possibility.*

McGrath et al (2011) offer crevasse drainage as the best means for the lower ablation zone. How much can reasonably be stored via this mechanism?

9.1. We have added **calculations that suggest that the retained or released meltwater is less than 1% of the ice sheet volume, see** Figure 5**. This agrees with published estimates of glacier macroporosity** (volume fraction of crevasses and fractures) that are around 1% (Anderson, 2004; Fountain & Walder, 1998; Harper & Humphrey, 1995). In other words, it is entirely possible that the meltwater amounts can be stored englacially. Some water may also be stored subglacially in the till (Fountain & Walder, 1998). Furthermore, other studies indicate that ice sheet meltwater retention and unfrozen water storage is possible over multiple years (Colgan et al., 2011).

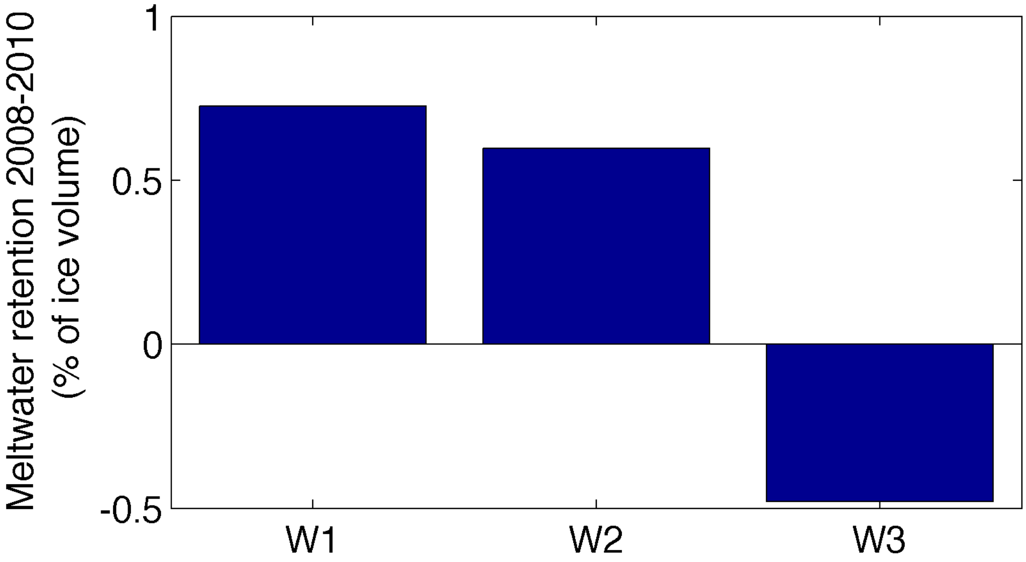

Figure 5. Meltwater retention from 2008 to 2010 as a percentage of ice volume for three ice sheet watershed delineations (see explanations for W1, W2 and W3 in Figure 1).

10. ***More problematic for the large values of retained meltwater [reported here] are the findings from van de As (2012) on the adjacent Kangerlussuaq*** *catchment. They found a good agreement between the calculated meltwater runoff and measured freshwater discharge in 2009 and 2010 both in timing and magnitude. Further they noted that total discharge was 8 and 19% lower than the calculated meltwater runoff similar to the 2009 measurements here.*

10.1. We discuss the discrepancy between our study and van As (2012) in comment 1.3. The discrepancy could be due to **scale, potential storage and, shorter observational period** at the Watson River. This is presented in the revised manuscript discussion

11. *Something seems out of place with 2010 and 2011* ***greater ablation usually would better activate the drainage system not enhance englacial storage****.*

11.1. See comment 1.2 and 16.1 regarding the possibility of getting ice sheet runoff and river discharge to agree for small catchments.

Response to comments by Pfeffer

12. *Concur with Pelto and ask* ***if the data can be trusted***
    12.1. See above in comments 1.1, 1.4, 1.8, 4.1, 9.1, and below in comments 18.1, and 18.2. Our revised manuscript provides better constrained uncertainty range for both catchment area, ice sheet runoff, and discharge estimates. With these improvements to the manuscript we still have evidence for meltwater retention and delayed release.
13. ***What are potential storages?*** *The area is below ELA so there is no multiyear storage capacity for freezing*
    13.1. See above in comment 9.1, **ice sheet macoporosity** can be around 1%, which implies that our meltwater retention/release values are feasible.
14. ***Is superimposed ice accounted for in this model?*** *Below the ELA, firn that becomes superimposed ice (water refrozen at the ablation surface) and infiltration ice (water refrozen in firn above the ablation surface) gets melted twice before running off, so if that isn't accounted for in the modeling, the energy expenditure on surface melt will indicate a lot more water leaving the system than actually occurs. How does Greull and Konzelmann (1994) handle superimposed ice?*
    14.1. Refreezing is included in the melt model. Also, the catchment is well below the ELA, so **there is no or very limited superimposed ice formation**. Regardless, this potential error is small due to the shallow snow cover in this part of the Greenland ice sheet. We have explained this in more detail in the current manuscript version.
15. *How well is the catchment area known?*
    15.1. The revised manuscript includes three possible catchment areas that lead to somewhat different results, but meltwater retention and delayed release is entirely possible with these revisions. Regardless, we have added a discussion of the catchment uncertainty. If the subglacial retention hypothesis is false, our results show convincingly that subglacial hydrology is highly variable from year to year: what goes in on one end, does not result in discharge along the same channels from year to year. See more in comments 1.4 and 1.4.
16. *Maybe it is impossible to make ice sheet runoff and stream discharge to agree for such a small catchment*
    16.1. An alternative conclusion for our data is that the effective ice sheet catchment for this small ice sheet area changes from year to year (see the good match between watershed W3 in 2008, between W1 and W2 in 2009 and 2010). Also see comment 1.2.

Response to anonymous Reviewer comments

17. Improve the possible sources of error in calculations and estimates

17.1. We have made improvements as requested regarding catchment delineations, runoff model, and discharge estimates as described in points both above and below in point 18.1 and 18.2.

18. Improve the description of ***the possible sources of errors in discharge estimates,*** *specifically by providing more detail of the methods to produce the data set, e.g. the number of times that the stream was manually gauged, and when these manual measurements were made, estimate the reliability of the summer rating curve for the winter period, consider rating curve uncertainty and local snowmelt provide equally plausible explanations for winter time losses. Water chemistry is needed to determine the source of the cold season meltwater losses.*

18.1. We have made back of the envelope calculations that suggest that **snowfall in this region is insufficient to explain the meltwater pulses**. This is presented in the revised manuscript as requested.

18.2. In the revised manuscript, **we have added new points for constructing the rating curve and now have a rating curve that is constructed with 35 points**. We have also created a simple model (using principles of Mannings equation that work reasonable well) to **estimate winter discharge** under the assumption that the entire channel below the water level sensor is frozen ice and water flows on top of this ice layer. This gives an extremely conservative lower boundary for what winter discharge may be, but one that is unlikely to take place. This revision suggests that cumulative ice sheet runoff from catchment W3 and the river discharge add up in year 3, while W1 and W2 remain unbalanced (Figure 6). This shows that only under extreme circumstances can the ice sheet meltwater budget is closed over a three year period. In this scenario also the early and late melt water releases becomes small and less important.

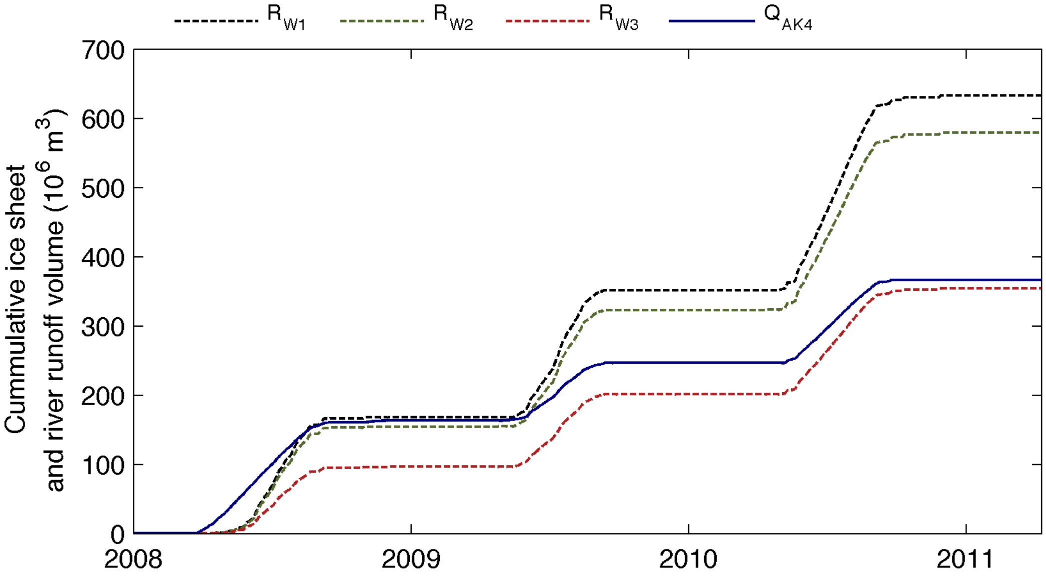

Figure 6. Same cumulative plot as in the previous cumulative figure, but with a more conservative method to estimate discharge during the cold season.

19. ***Quantify the uncertainty with model runoff*** *calculations, provide a more* ***comprehensive description*** *of the model, provide an error term for modeled runoff*
    19.1. The revised manuscript contains a more comprehensive model description and error term.
20. ***Better constrained catchment area uncertainty****, quantify influence of ASTER GDEM vertical errors, Provide information about ASTER GDEM spatial resolution, Improve the uncertainty estimate from lacking basal topography*
    20.1. See above for how we have better constrained the catchment area and included basal topography. **The Aster DEM errors are small and do not impact the melt calculations (Van As and others, 2012),** and are unlikely to have a large impact on the catchment area. We have included text to describe this in the revised manuscript
21. *Reviewer provides several minor corrections/suggestions for improving the manuscript.*
    21.1. These corrections have been implemented as requested with the possible exception of the naming of the sites since that naming convention is already established in other manuscripts.

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