General comments, referee 3

General comment 1: The paper presents hydrometerological dataset for one year and water balance calculations based on collected data. It identifies and analyses qualitatively and quantitatively the processes of water balance formation of small lake and its catchment. The weakest point of the study is a short time period of data – only one year. It hardly could be used for comprehensive data analysis, the identification of dominant hydrological processes and the evaluation of water balance components and their uncertainties with high degree of confidence.

Answer: The focus of this study is on the quantification of intra-annual variation and uncertainties of water levels and fluxes, and other components of the cumulative net water balance over the given investigation period. The aim was not to assess a representative long-term average water balance and its associated flux components. The relatively small catchment is well investigated, even though the data set is limited in terms of spatial and temporal extent. Relevant fluxes and processes have been measured with high temporal resolution, and given the small size of the catchment, 1.56km^2, also the spatial resolution is high. Evapotranspiration is not measured directly, which is rather typical, but we did measure all parameters needed to calculate the potential evapotranspiration with the Pennman-Monteith formula. The study addresses how to conceptualize and quantify the main hydrological flows and processes in the catchment during the investigated hydrological year and the uncertainties that still remain even with an extensive measured dataset for such a limited time period; this uncertainty assessment is also important for long-term average conditions, as the uncertainties of each year combine to the total ones over the long-term period. The limitation, relative to long-term average conditions, of this study considering only a period of one year was assessed by relating the local values of precipitation to the long-term average values obtained from the nearby Kangerlussuaq station. In addition, we compare also in the revised manuscript local air- and soil temperature data to corresponding long-term values from the Kangerlussuaq station.

We realize that we did not sufficiently explain the focus of the present water balance study, and have reformulated the introduction of the revised manuscript to do so, as follows:

"The present study focuses on the short-term (intra-annual) variability of the linked surface and subsurface hydrological flows and processes in an arctic permafrost catchment in western Greenland. For this catchment, we present a new hydrological dataset, as a controlled field experiment carried out within the relatively small catchment area (1.56km^2) over a relatively short investigated time period (1 year). The spatial and temporal investigation resolution, however, is relatively high within this small area and short time period. This dataset resolution, for many relevant hydrological processes, enables quantification of the net cumulative water balance over the investigation period with a relatively high degree of confidence, considering also the links between surface waters and both supra-permafrost and sub-permafrost groundwater, and between the small catchment and its associated lake talik. Even with such an extensive measurement programme, however, some key uncertainties still remain, and a main study aim is to bound and assess these remaining uncertainties in the quantification of main hydrological flows and net water balance of the study area. For this purpose a conceptual model of the relevant hydrological system is constructed, which can also be further used as a basis for modeling of the permafrost hydrology in this area."

Also the conclusions have been revised in the following way:

“The work highlights the importance of developing a conceptual understanding of hydrological flow variability in a catchment during different time periods within a year. We have shown how this understanding together with the detailed site-specific hydrological data can be used to quantify uncertainties still remaining despite a comprehensive investigation programme. By analysing data from the one-year-study, we can conclude that investigations of snow dynamics (sublimation and snow blowing events) are needed to reduce the identified uncertainties of the water balance. Sublimation from snow and snowdrift are key processes in the water balance during the frozen period. As a consequence of the snowdrift, the precipitation affecting the catchment differs from that affecting the wind exposed lake area when ice is covering the lake.

Based on the hydrological measurements that link the surface and subsurface water systems below the permafrost, we conclude that the water flow between lake and talik is very small relative to the other water balance components, and that for the hydrological year 2011-2012, water from TBL recharges the deeper talik groundwater. Our results support the hypothesis that relative topographical location governs the direction of groundwater flow in a talik. Temporal pressure changes in the talik closely reflect the measured local hydrological processes at the lake surface rather than any larger-scale regional processes in the ice-sheet dominated landscape. These results indicate the investigated catchment hydrology as being rather independent from catchment-external landscape features, including those of the close-by ice sheet.”

General comment 2: The uncertainly estimation of defined water balance components seems to be based on pure assumptions of possible error sources that do not lead yet to using additional data or conducting new measurements. Why did not the authors consider calculated PET, the assumption of invariable lake area, the processes of water freezing and thawing in active layer and existence of Ral during the part of the frozen period as possible sources of uncertainty?

Answer: The performed uncertainty analysis accounts for that different possible flow paths for groundwater and surface water during the frozen and active period result from the dynamics in the active layer when water is freezing and thawing. During the frozen period, surface water inflow/outflow is not possible for the water exchange between the lake and the active layer, and the only possible flow path for R is groundwater exchange with the underlying talik, R_{gw}. When studying the time series of R, however, outflow of water from the lake during the frozen period was observed that could not only be associated with R_{gw}. To identify the related sources of uncertainty in the calculated time series of R, three different possible interpretation cases were conceptualized, considering precipitation, evapotranspiration and groundwater exchange with the underlying talik feature as the main uncertainty possibilities. For evapotranspiration, the calculated PET was then indeed assumed as a possible source of uncertainty, with the result being that the calculated PET for the frozen period could be underestimated by approximately up to a factor of 2. The Pennman-Monteith formula does account for sublimation, but the sublimation is underestimated and has to be corrected for the frozen period when applying it to Arctic sites. In the revised manuscript we have described more clearly that case 2 does indeed analyse the possible uncertainty in the calculated time series of PET. Given the geometry of the lake and its catchment, the uncertainty associated with the assumption of a constant lake area is insignificant compared to other sources of uncertainty analysed in cases 1-3.

General comment 3: The paper in present shape does not significantly contribute to the understanding of the Arctic hydrological system. Possible ways of increasing the scientific importance of the research could be an extension of the studied period, upscaling the results to larger areas and/or involvement of additional data and methods (isotopes, mathematical modelling, etc.)

Answer : We of course agree that further analyses of chemical data and including numerical modelling are of great interest. However, this study does not include analysis of chemical data (isotopes, electrical conductivity, etc) because the chemical data cannot be properly and conclusively interpreted without first understanding and quantifying the main hydrological fluxes, processes and remaining uncertainties at the studied catchment site over the investigated time period (rather than on average over some long-term period). The purpose of the present study is to do these hydrological quantifications, as necessary basis for further analysis of the linked hydrology-chemistry data and interactions at the site over the time period of measuring both aspects. Understanding the hydrology of the site over this measurement period is instrumental for being able to interpret and analyse the concurrent chemical data set. A detailed analysis of time series data and a conceptual interpretation model for this data is also needed for setting up a more detailed numerical hydrological model of the site. The present study focuses on providing the hydrological interpretation-conceptualisation basis from all collected hydrological data that is needed for further chemical and detailed numerical studies.

We consider and use the space-time specificity of the present hydrological study as a controlled field experiment. The analysis of this experiment provides a new, rather extensive and high-resolved data set within the experimental space-time boundaries. This data set includes only locally measured data in order to describe and quantify the main hydrological flows and processes, and their remaining uncertainties in spite of the extensive available data, within the studied catchment and time period. The aim is thus not to extrapolate the data for general representation of any long-term average water balance, and its components, over some large arctic area.

To our best knowledge, interactions between soil/groundwater in the active layer, surface water (here in the lake) and groundwater in the sub-permafrost system (here in the talik below the lake) have not previously been quantified by using only locally measured data from a small well investigated catchment as in this study, rather than e.g. meteorological data from some regional station several kilometres away for the actual site. In addition, locally measured data show that surface processes, such as evapotranspiration and snow dynamics, also govern the head variations in the deeper groundwater system in the talik below the lake.

The revised manuscript states now more clearly that "This work has focused on hydrological data analysis, as a necessary basis for forthcoming work, aimed to link the here quantified hydrological conditions and their uncertainties with interpretation of the isotopic composition of lake water and groundwater in the active layer and in the borehole, and to numerically simulate the linked hydrological and hydrochemical conditions. Such forthcoming research and its results can in turn be used to further test and reduce remaining uncertainties about the present data-driven hydrological conceptualisation and quantification of the site, and also simulate conditions beyond the time period of present field data."

Specific comments and questions:

1. **Section 2.1** includes many details about the catchment's climate, geology and topography that are not used for further analysis. It does not contain any information about active layer depth and its variability within the catchment that seem to be important for evaluation of Ral.

Answer: The section aims to give an overview of the site and to describe its overall conditions. Details about climate, hydrology and active layer depth are described in section 2.2.2. We agree that some information about the active layer depth in the region has been missing and will in the revised manuscript add the following text to row 14 P9276 of the original manuscript:

“The active layer in the area between Kangerlussuaq and the ice sheet margin has a thickness of 0.15-5m (van Tatenhove and Olesen, 1994). Areas in sandy inorganic soils with discontinuous vegetation tend to have warmer soil temperatures (deeper active layer) than organic soils covered with dense vegetation.”

2. **Section 3.1 and Fig.5:** The term “conceptual model” usually refers to mathematical models that use simple empirically-derived equations for the process representation. It’s better to use the term “perceptual” or “descriptive” model for description of hydrological system that the authors present in Section 3.1 and Fig.5.

   Answer: We do not agree. Conceptual model can be used in several ways. In the present context, conceptual model refers to a geometrical description of the problem to be solved, with key processes identified and quantitatively described. This definition is in line with the reference (R-03-08, p. 19), which states:

   Conceptual model: A model which defines the geometric (or structural) framework in which the problem is to be solved, the size of the modeled volume (scale), the constitutive equations (mathematical model) for the processes included in the model and the boundary conditions. (In some literature “conceptual model” also includes what is here called “Descriptive model”.)

   Ref: Hydrological Site Descriptive Model - a strategy for its development during Site Investigations. Rhén, I., Follin, S., Hermanson, J., Svensk Kärnbränslehantering AB.Report R-08-03. 2003

3. **Section 4** should also include a comparison of presented results with similar studies from other catchments.

   Answer: The data set presented here contains monitoring data from a cored borehole down to 200 m depth where groundwater pressure in the unfrozen groundwater of the talik is measured, hydraulic head in the lake, soil moisture content variation in space and time and local meteorological data. To our best knowledge there are no studies where the interactions between supra-permafrost and sub-permafrost groundwater, as well as their interaction with surface water (here the lake), have been quantified based on actual locally measured time series data. Previous studies, referred to in the manuscript, focusing on numerical modelling, have shown the more general dynamics of these interactions.

   In this study, we address how to conceptualize and quantify the main hydrological flows and processes in a catchment during a hydrological year. We further also assess the uncertainties that still remain, even with availability to an extensive site-specific dataset. In the revised manuscript we have updated the introduction to make the aim and focus of the study clear, see answer to general comment no 1 above.

4. **Page 9273, line 29:** The authors could cite some of mentioned “few previous studies”.

Answer: The sentence refers to the studies summarized on lines 22-29 P9273.

5. **Page 9276, lines1-3:** Does slope aspect and inclination influence the precipitation, vegetation and active layer depth?

   Answer: In this relatively small catchment, liquid precipitation is evenly distributed over the catchment and is not influenced by slope or inclination. However, precipitation falling as snow is not evenly distributed due to strong winds in the area redistributing the snow.

   The active layer depth is more influenced by soil type and vegetation cover than by slope aspect and inclination. The active layer depth is thinner in the valleys covered by organic soils and more dense vegetation. Along the hill sides in the till areas (blue areas in Figure 1B), the active layer depth is thicker. In the area mentioned on lines 1-3 P9276, the active layer has a maximum thickness of approximately 70 cm. Information about the active layer depth variation in the catchment is added to section 2.1 in the revised manuscript, see above.

6. **Page 9276, line 10:** What is a depth of the drilling? Does it confirm the presence of open talik?

   Answer: The depth and length of the borehole 191.5 m and 221 m respectively as indicated on P9279 line 17-18 in the original manuscript. In the revised manuscript under section 2.2.2 the part "Active layer and lake ice" will be changed to "Permafrost, active layer and lake ice", and start as follows (P9278 L10 in the original manuscript):

   "Permafrost, Active layer and lake ice

   Temperature profiles from a borehole, DH-GAP03 (Harper et al, 2011), situated between the ice sheet and TBL, but at approximately 150 m higher altitude, indicate a permafrost depth of c 335 m. The mean temperature along the upper 200 m of this borehole was -2.9°C in September 2009. A 221 m long borehole, DH-GAP01 (Fig.1), was drilled in a 60° inclination under the TBL, reaching a vertical depth relative to the top of casing (TOC) of 191.5 m. Based on temperature data from the borehole, the upper 20 m of the borehole is considered to be in permafrost. The transition from frozen to unfrozen ground coincides with the lake shoreline, i.e., temperature data indicates a talik being maintained under the lake. The mean temperature in the bedrock under the lake is 1.25°C. There are no indications of decreasing temperatures in the deepest part of the borehole indicating a closed talik. Geothermal modelling of the DH-GAP01 borehole supports the hypothesis that the investigated lake has a through talik beneath it, penetrating the 300 m deep permafrost (Harper et al, 2011). The temperature in DH-GAP03 at a vertical depth of 191 m, i.e at the same depth as the maximum depth of the DH-GAP01 borehole under TBL, was measured to -2°C."

7. **Page 9277, line 13, Table 3:** How was the precipitation correction factor determined?

   Answer: The correction of precipitation follows the methodology described in Alexandersson (2003). Alexandersson used 878 meteorological stations in Sweden in order to classify them to get comparable precipitation measurements over different wind exposed areas. The location of the precipitation gauges is classified in order to seven classes ranging from “Ideal location, for example in a garden or wooded area with moderately high shrubs or hedges near the gauge” to “Extremely open location, on the outskirts of the archipelago, rocky island, bare mountain region above the tree line”. The precipitation gauge at TBL is placed in class number 6 “Very open location, mostly coastal strips or mountain areas.” For class number 6 the correction term for the wind loss is 33% for snow and 12% for rain, losses due to adhesion is corrected with 0.1mm for each precipitation event.

In the revised manuscript, the correction of precipitation and the different classes mentioned above are described in more detail in the Supplementary material.

8. **Page 9282, line 5-8:** Do the authors have any evidence of described process of lake water flowing into active layer in transition period between “active” and “frozen” periods? Did the authors consider possibility of opposite-direction process – push-out of water in active layer during the ground freezing?

   Answer: We don’t have any evidence for this process, or the same process in the opposite direction. The dynamics in the transition zone between the terrestrial areas and the lake is not investigated. Since we don’t have evidence of the process, we mention it as a possible, but not very likely, event. We will remove the text on lines 5-8 P 9282 from the manuscript.

9. **Page 9282, line 15:** Did the authors use 2–5*10^{-8} ms^{-1} as the values of K? How could the authors assess the uncertainty associated with K except water balance calculations?

   Answer: The K-values were determined by analysing data from a hydraulic test performed in the borehole below the lake (P9279 L26). Two pressure-response tests associated with water withdrawal were performed in September 2010. When water was removed from the borehole, the pressure responses were monitored. The pressure recovery data were evaluated using the following commonly employed methods: Cooper-Bredehoeft-Papadopulos (Cooper et al. 1967), Bouwer-Rice (Bouwer and Rice 1976) and Hvorslev (1951).

   2-5*10^{-8} m/s are the hydraulic conductivity values used in the base case of the annual water balance calculations. In the uncertainty cases, case 3 is focusing on the groundwater exchange with the talik. If the calculated R during the frozen period from the base case ware only associated with $R_{gw,}$ the hydraulic conductivity of the bedrock would have to be one order of magnitude higher. However, the groundwater exchange with the underlying talik is small relative to other water balance components, even if the higher K-value is used in the calculations.

   A main outcome of our study is that there is contact between the deep groundwater system in the talik and the surface water. The intra-annual variations of the hydraulic head in the borehole seem to be governed by surface processes such as evaporation and snow dynamics. The calculated exchange of water is low and, during the studied period, a downward directed gradient has been observed. In the revised manuscript the following text is added (to current P9289 L12): “The recharge/discharge conditions between the lake and the underlying talik are likely to be dynamic in time.”, implying that water flow may switch between recharge and discharge at the lake-talik boundary”

10. **Page 9276, line 21;** page 9280, line 13; page 9282, lines 20-21: How did the authors estimate the PET? As it can be understood the authors assumed that actual ET is

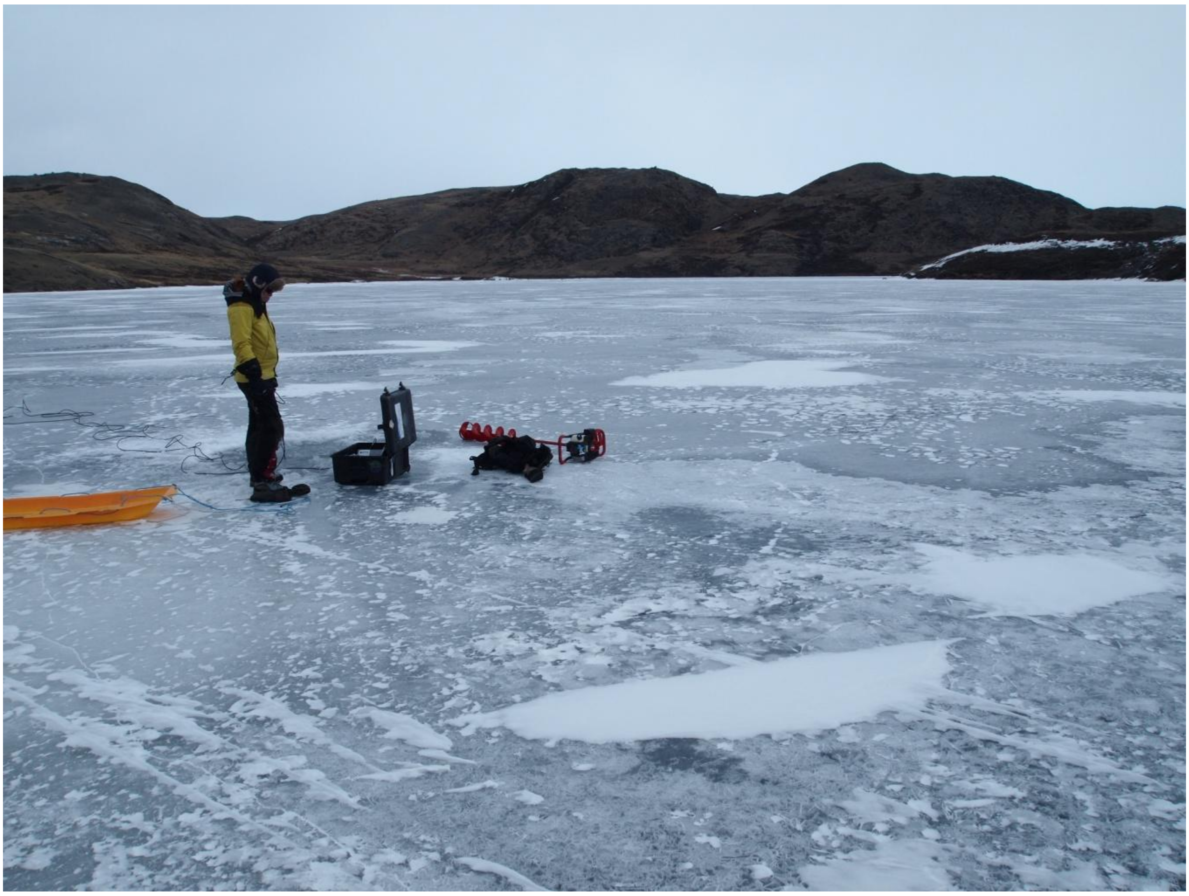
equal to the PET which may be questionable for the frozen period when the lake surface is covered by ice and snow and the air temperature is negative.

Answer: In the Supplementary material L23-27 it is described that the PET is calculated using the Penman-Monteith formula. Data on air temperature, air pressure, relative humidity, net radiation and wind speed from the local AWS were used in the calculations.

We do agree that the accuracy of the Penman-Monteith formula is questionable during the frozen period. Sublimation is most probably underestimated. This is also why the frozen period is studied in detail in one of the three uncertainty cases. One main conclusion of the work is that sublimation from snow is a key process in the water balance for the frozen period and underestimated in the original calculations of PET. For case 2, section 3.3.2, we state that the calculated time series of PET had too low PET values for the frozen period and that the PET had to be multiplied by approximately a factor of 2 to balance the equation.

11. **Page 9287,** 2nd paragraph: Suggested relationship between the decrease in lake water head and the number of wind events should be further checked, for example by using the information from the time lapse camera.

    Answer: Time lapse photos from the studied hydrological year are not available for period 2 shown in Figure 8. However, the process of snow disappearing from the lake due to snow blowing events and sublimation has been observed during other periods; one example is shown in the photos below. The photos are taken on April 24 and April 25 2013, a period with an hourly mean temperature of -3°C ranging from -0.23 to -4.93. During the period April 24-25, strong winds with a mean hourly wind speed of 5.1m/s were recorded; almost all snow present on the lake on April 24 disappeared. The photos below will not be included in the revised manuscript since they are taken from a period not included in the studied hydrological year.



12. **Page 9290, line 23:** The conclusion about the importance of sublimation from snow and snow drift in water balance during the frozen period seems to be not enough justified because these values were determined as the residuals in water balance calculation for studied year.

Answer: If snow sublimation is not taken into account, and only using calculated PET values from the Pennman-Monteith equation, the sublimation is most probably underestimated. Since sublimation was one of the components not measured in the field during the studied period, the uncertainty analysis aimed at determining the highest possible magnitude of this missing component in the water balance during the frozen period. This together with the lake dynamics shown in Figure 8 indicate snow sublimation and snow blowing events as potential important processes, which then have to be considered when calculating water flows and balances in Arctic catchments.

In Figure 8 we show that the hydraulic head is changing, both over the lake and in the borehole, due to increased or decreased load (caused by snow) on the lake ice. The decrease in snow load cannot be associated with snow melting events only; the load is decreasing during certain periods even though temperature below zero °C prevails. Processes that can explain the observed falling hydraulic head is snow drift and/or sublimation; these processes are discussed in section 4.1.

13. Figures 2, 3 and tables 1, 4 are not necessary as they do not contribute to the manuscript substantially. Figure 6 could be more informative if the precipitation and SWE added.

Answer: Figure 2 helps the reader to get an overview of the applied methodology and conceptualisation of the hydrological system.

Local time series data of relevant parameters is one of the main contributions of the present study. To our opinion it is therefore important to show and share the data used in the analysis. In figure 3, the soil temperature regime and thawed depth of the active layer is shown; the thawed depth is a key factor for the runoff into the lake as well as for infiltration of snowmelt water. Since sublimation and wind drifting snow have been shown to be important processes, Figure 3B also makes sense in order to show the dominating wind direction coming from the Ice Sheet and carrying dry cold air into the catchment area.

In table 1 the reader gets information about the lake catchment geometry. This information is important for assessing the representativity of the spatial data density, e.g., regarding one observation point for meteorology as sufficient given the size of the catchment.

The information in Table 4 defines the periods of frozen and thawed conditions needed in the conceptualisation of the hydrological system. It is referred to in several different sections in the text; excluding it would generate repetition of information and a more difficult text to read.

In the revised manuscript, precipitation and SWE have been added to Figure 6.

14. **Technical corrections: Figure 7:** All calculations in the paper are presented in mm, but the Fig.7 shows m3/year. It complicates the understanding of the Figure 7.

Answer: The reason for presenting the calculations in m^3/y is that the corresponding values in mm can be and are normalized over different areas (that of the lake and that of the catchment). A new version of the Figure is provided in the revised manuscript, with all values given in mm/y, and with clear notes of which values are then normalized by which area.