

AUTHORS' RESPONSE TO REVIEWS OF:

Journal: HESS

Title: Differences in the water-balance components of four lakes in the south-central Tibetan Plateau

Authors: S. Biskop et al.

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Dear Prof. Su,

in the following pages we provide a point-by-point reply to the referees comments. Referees comments are given in italic while our replies are in roman. The previous version of our manuscript is referred to as V2. In addition, we provide a manuscript version showing the changes we made to the text.

Thank you for considering our manuscript for final publication in HESS.

Sophie Biskop and co-authors

POINT-BY-POINT RESPONSES TO ANONYMOUS REFEREE #1

Section 4.1.1, I'm happy to see this evaluation part. However, I'm not convinced by the results as shown in Fig 3. The correlation coefficient of 0.81 does not make any sense here. Actually, there are very large discrepancy between the model results and in-situ measurements. The absolute deviation between observed and simulated relative changes of monthly-averaged lake levels varies between -0.31 m and 0.3 m. If look at Table 4, we can find that the modeled annual rate for Nam Co is about 0.24m which is of the same order of magnitude as above mentioned model errors. Therefore, how can we believe you model results especially for the period between June and November? Please take this major concern into account and give your explanation.

RESPONSE: We are not sure if the reviewer misunderstood the meaning of the correlation coefficient. The correlation coefficient of 0.81 indicates that the model is able to represent the overall seasonal lake-level dynamic during the June-November period (V2 P11 L27-29), but says nothing about the absolute deviations between model simulations and observations. The absolute deviation between observed and simulated relative changes of monthly-averaged lake levels during the June-November period is largest in the year 2006 (-0.31 m) and 2009 (0.30 m). In the year 2007, 2008 and 2010 the absolute deviation is 0.16, 0.01 and 0.08 m, respectively. The absolute deviation between observed and simulated relative changes during the June-November period averaged over the years 2006 to 2010 is approximately 0.05 m. As already discussed in the manuscript (V2 P20 L29-31; V2 P23 L16-17), a non-systematic error pattern in the HAR10 precipitation data might be the reason for larger deviations between simulated and measured lake levels of the Nam Co in specific years (Fig. 3). In our opinion, it is difficult to compare the absolute deviation between modeled and observed relative changes of monthly-averaged lake levels during the June-November period of specific years with the modeled mean annual lake-level change rate of the entire 10-year study period (2001-2010).

POINT-BY-POINT RESPONSES TO ANONYMOUS REFEREE #2

Authors have made a lot of efforts to improve the manuscript. The purpose is clarified focusing on the differences in the water-balance components of four lakes. Concerns of reviewers are responded clearly in the point-to-point response and revision. Generally, it is publishable after minor revision.

P5L18-21, it is claimed that “The cold bias effect on the accuracy of the hydrologic-modeling results is assumed to be low”. This sentence should be considered further. A great cold bias in winter is found in previous regional climate simulations in the TP just as Maussion (2014) mentioned. The larger cold bias in winter than in summer could cause great influence in simulations, for instance more snow in winter than in summer.

RESPONSE: The precipitation amount during the dry cold winter season is low and precipitation falls primarily as snow. Therefore, we still believe that a possible winter cold bias has a low influence on the model results that are relevant for this study (e.g., land runoff).

Another noticeable point is simulated precipitation is great overestimated in winter than in summer in the TP. However, the same precipitation-scale factor was utilized on the entire 10 years. The same precipitation-scale factor will lead to a still overestimated precipitation in winter and underestimated precipitation in summer. This could be one reason for the overestimated SCAF in winter and underestimation in summer on Section 4.1.2 and P22. As a result, L18-19 on P23 should be reconsidered.

RESPONSE: There is no evidence for overestimation of precipitation in winter. We think that the omission of processes such as snow redistribution by wind and avalanches and snow loss by blowing-snow sublimation has a larger influence on seasonal snow-cover patterns than errors related to the precipitation-scaling factor.

The last sentence on P11, “the model overestimates the lake level for the month of November” is not right for 2006 and should be more specific.

RESPONSE: We considered it in the revised manuscript.

P19L21, it should be “4.6% and 1.8%”rather than “4.6 and 1.8%”.

RESPONSE: Done.

POINT-BY-POINT RESPONSES TO ANONYMOUS REFEREE #4

The authors have substantially improved the quality of the manuscript. They have added considerable content about the interpretation of model outputs (role of glaciers, section 4.2.2) and about the discussion of factors potentially controlling the the lake-level variability (permafrost thawing, past lake level changes, section 5.1.2). I think the manuscript meets the requirement of HESS after minor corrections suggested below.

P. 17, l. 30 : "slightly higher...considering the percentage of basin area covered by glaciers"

I suggest "... considering also the lower percentage of basin area covered by glaciers in our study basins". Remove "slightly".

RESPONSE: We rephrased this sentence following the Reviewer's recommendation.

P. 18, l. 6: Please add in brackets a reference to the paper section where the values are provided.

RESPONSE: Done.

P. 18, l. 24: "A decreasing trend in potential evaporation before 2000 might have resulted in rising lake levels in the central TP."

This is not clear from the wording. Is this decreasing trend a hypothetical assumption or has it been observed? Please rephrase.

RESPONSE: We added a previous sentence: "The potential evaporation decreased in most areas on the TP during 1961-2000, primarily caused by decreasing wind speeds (Xie & Zhu, 2013)".

P. 19, l.11: "The water contribution from permafrost will become limited when ground temperature increases above the melting point of the frozen soil."

The formulation is not concise. The water contribution does only become limited after a long period of permafrost thawing, I assume. An not "when ground temperature increases above the melting point". Please rephrase.

RESPONSE: We rephrased this sentence as follows: "The water contribution from permafrost will become limited when ground temperature remains above the melting point of the frozen soil and the water held in the frozen soil has been released (Li, Y. et al., 2014)."

P. 23, l. 14: Maybe state here which type of satellite data were used.

RESPONSE: We added a reference to the paper section where the data are described.

P. 23, l. 16: "should be considered carefully".

I guess you mean "should be interpreted with care"

RESPONSE: We rephrased this sentence following the Reviewer's recommendation.

P. 23. l 18: "uncertainties which appear to be related to the precipitation-scaling factor, should not affect the overall conclusions drawn from the model-application results"

This is a bold statement, considering that using different precipitation scaling factors would indeed affect the overall conclusions (Figure 2). I recommend adding a short sentence explaining how uncertainty was constrained.

RESPONSE: We changed the sentence to "uncertainties which appear to be related to the precipitation-scaling factor should not affect the overall conclusions drawn from the model-application results, as discussed in Sect. 5.2."

Differences in the water-balance components of four lakes in the south-central Tibetan Plateau

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Abstract

The contrasting patterns of lake-level fluctuations across the Tibetan Plateau (TP) are indicators for differences in the water balance over the TP. However, little is known about the key hydrological factors controlling this variability. The purpose of this study is to contribute to a more quantitative understanding of these factors for four selected lakes in the south-central part of the TP: Nam Co and Tangra Yumco (increasing water levels), and Mapam Yumco and Paiku Co (stable or slightly decreasing water levels). We present the results of an integrated approach combining hydrological modeling, atmospheric-model output and remote-sensing data. The hydrological model J2000g was adapted and extended according to the specific characteristics of closed-lake basins on the TP and driven with “High Asia Refined analysis (HAR)” data at 10 km resolution for the period 2001-2010. Differences in the mean annual water balances among the four basins are primarily related to higher precipitation totals and attributed runoff generation in the Nam Co and Tangra Yumco basins. Precipitation and associated runoff are the main driving forces for inter-annual lake variations. The glacier-meltwater contribution to the total basin runoff volume (between 14 and 30 % averaged over the 10-year period) plays a less important role compared to runoff generation from rainfall and snowmelt on non-glacierized land areas. Nevertheless, using a hypothetical ice-free scenario in the hydrological model we indicate that ice-melt water constitutes an important water-supply component for the Mapam Yumco and Paiku Co, in order to maintain a state close to equilibrium; whereas, the water balance in the Nam Co and Tangra Yumco basins remains positive under ice-free conditions. These results highlight the benefits of

1 linking hydrological modeling with atmospheric-model output and satellite-derived data, and
2 the presented approach can be readily transferred to other data-scarce closed lake basins,
3 opening new directions of research. Future work should go towards a better assessment of the
4 model-chain uncertainties, especially in this region where observation data are scarce.

5

6 **1 Introduction**

7 The drainage system of the interior Tibetan Plateau (TP) is characterized by numerous closed-
8 lake (endorheic) basins. Because an endorheic lake basin integrates all hydrological processes
9 in a catchment, lake-level or volume changes provide a cumulative indicator of the basin-
10 scale water balance. While most of the lakes located in the central part of the TP are
11 characterized by a water-level increase over recent decades (e.g., Zhang, et al. 2011; Phan et
12 al., 2012), there are also several lakes with nearly stable or slightly decreasing water levels in
13 the southern part of the TP. These high-elevation lakes are therefore considered to be one of
14 the most sensitive indicators for regional differences in the water balance in the TP region
15 (e.g., Zhang, B. et al., 2013; Zhang, G. et al., 2013; Song et al., 2014).

16 Neglecting the influence of long-term storage changes such as deep groundwater and lake-
17 groundwater exchange, the net water balance of an endorheic lake basin with water supply
18 from glaciers can be expressed as: $\Delta V_{\text{lake}} = P_{\text{lake}} - E_{\text{lake}} + R_{\text{land}} + R_{\text{glacier}}$, where ΔV_{lake} is the
19 lake-volume change (net annual lake-water storage), P_{lake} the on-lake precipitation, E_{lake} the
20 evaporation rate from the lake, and R_{land} and R_{glacier} are the runoff from non-glacierized land
21 surface and from glaciers (in units of volume per unit time). Under constant climatic
22 conditions, endorheic lakes will eventually tend towards a stable equilibrium ($\Delta V_{\text{lake}} = 0$),
23 where the several water-balance terms are balanced (Mason, 1994). Lake-level changes thus
24 result from a shift in the water input or output.

25 Due to the accelerated glacier mass loss, it has been hypothesized that lake-level increases are
26 primarily due to an increased inflow of glacier meltwater (e.g., Yao et al., 2007; Zhu et al.,
27 2010; Meng et al., 2012). Nevertheless, glacier runoff into lakes itself should not increase the
28 overall water-volume mass on the TP, as indicated by GRACE satellite gravimetry data
29 (Zhang, G. et al., 2013). Furthermore, numerous lakes of the TP are not linked to glaciers
30 (Phan et al., 2013), and the water-level changes of lakes without glacier meltwater supply in
31 the 2000s were as high as those of glacier-fed lakes (Song et al., 2014). In other studies,
32 increased precipitation and decreased evaporation were generally considered to be the

1 principal factors causing the rapid lake-level increases (e.g., Morrill, 2004; Lei et al., 2013;
2 2014). Li, Y. et al. (2014) argued for the importance of permafrost degradation on recent lake-
3 level changes. Thus, recent studies addressing the controlling mechanism of lake-level
4 fluctuations remain controversial.

5 In order to explore differences in the water balance of endorheic lake basins in the TP region,
6 recent studies emphasize the urgency of the quantification of water-balance components by
7 using hydrological models (e.g., Cuo et al., 2014; Lei et al., 2014; Song et al., 2014).
8 Hydrological modeling studies of endorheic lake basins in the TP region are rare (e.g., Krause
9 et al., 2010), principally due to a lack of hydro-climatological observations and limitations in
10 spatial and temporal coverage of available gridded climate data (Biskop et al., 2012). The
11 paucity of spatial information of climatological variables was addressed by Maussion et al.
12 (2014) who developed a high resolution (up to 10 km x 10 km) atmospheric data set for the
13 2001-2011 period, the “High Asia Refined analysis (HAR)”. The HAR10 data set was
14 successfully applied in surface energy balance/mass balance (SEB/MB) modeling studies
15 (Mölg et al., 2014; Huintjes et al., 2015) and in a hydrological modeling study in the Pamir
16 Mountains (Pohl et al., 2015), but has not yet been used as input for catchment-scale
17 hydrological modeling studies in the central TP. The objective of this study is the
18 hydrological modeling of endorheic lake basins across the southern-central part of the TP in
19 order to:

- 20 i) analyze spatiotemporal patterns of water-balance components and to contribute
21 to a better understanding of their controlling factors,
- 22 ii) quantify single water-balance components and their contribution to the water
23 balance, and obtain a quantitative knowledge of the key factors governing the
24 water balance and lake-level variability during the 2001-2010 period.

25 The lakes Nam Co and Tangra Yumco with increasing water levels (i.e. positive water
26 balance) and the lakes Mapam Yumco and Paiku Co with stable or slightly decreasing water
27 levels (i.e. stable or slightly negative water balance, respectively) were selected to investigate
28 differences in the water-balance components. The paper is organized as follows. In Sect. 2,
29 we describe the study area and the data used. Section 3 gives details of the hydrological
30 modeling approach and in Sect. 4, we present the modeling results and assess similarities and
31 differences among the basins; in Sect. 5, the results, limitations and uncertainties of this study
32 are discussed with respect to findings from other studies. Finally, Sect. 6 highlights the

1 principal results and concludes with remarks on future research needs and potential future
2 model applications.

3

4 **2 Study area and data**

5 **2.1 Description of the study area**

6 The study region comprises four endorheic lake basins along a west-east (W-E) lake transect
7 in the south-central part of the TP between 28°N~32°N and 81°E~92°E (Fig. 1). Basic
8 characteristics of the selected lake basins are summarized in Table 1. Climatologically, the
9 study region encompasses a semi-arid zone and is characterized by two distinct seasons: a
10 temperate-wet summer season dominated by the Indian Monsoon and a cold-dry winter
11 season determined by the Westerlies. The mean annual air temperature (MAAT) lies between
12 0°C and -3°C and the mean annual precipitation ranges between 150 and 500 mm, with 60-80
13 % of this total occurring between June through September (Leber et al., 1995). The study
14 region features a climate gradient, with increasingly cooler and drier conditions in a westward
15 direction.

16 Due to the semi-arid and cold climate conditions as well as the complex topography, soils in
17 the study area in general are poorly developed and vegetation throughout the study area is
18 generally sparse. The growing period lasts approximately five months, from late April/early
19 May to late September or mid-October (Zhang, B. et al., 2013). The highest mountain regions
20 are covered by glaciers and permanent snow. Among all basins, the Paiku Co catchment
21 exhibits the largest glacier coverage (6.5 % of the basin area). The area covered by glaciers in
22 the Nam Co, Tangra Yumco and Mapam Yumco basins accounts for 2 %, 1 % and 1.5 % of
23 catchment area. The lake area in the several basins corresponds to 18 % (Nam Co), 11 %
24 (Mapam Yumco), 9.5 % (Paiku Co) and 9 % (Tangra Yumco). Based on GLAS/ICESat data,
25 the lake levels for Nam Co and Tangra Yumco rose by approximately 0.25 m yr⁻¹ between
26 2003 and 2009; whereas, the lake levels for the Paiku Co and Mapam Yumco slightly
27 decreased by around -0.05 m yr⁻¹ (Zhang et al., 2011; Phan et al, 2012).

28 **2.2 Data used**

29 Because of limited availability of climatological data in the TP region, we used a new
30 atmospheric dataset for the TP, the “High Asia Refined analysis (HAR)” (Maussion et al.,

1 2014) as input for the hydrological model. The HAR data sets were generated by dynamical
2 downscaling of global-analysis data (Final Analysis data from the Global Forecasting System;
3 dataset ds083.2), using the Weather Research and Forecasting (WRF) model (Skamarock and
4 Klemp, 2008). A detailed description of this procedure is given in Maussion et al. (2014).
5 HAR products are freely available (<http://www.klima.tu-berlin.de/HAR>) in different spatial
6 (30 km x 30 km and 10 km x 10 km) and temporal (hourly, daily, monthly and yearly)
7 resolutions. In this study, we used the daily HAR10 data. In the WRF model version 3.3.1,
8 which was used for the generation of the HAR10 data, the lake-surface temperature is
9 initialized by averaging the surrounding land-surface temperatures. By analyzing the
10 influence of the assimilation of satellite-derived lake-surface temperatures, Maussion (2014)
11 found that the standard method of WRF leads to a much cooler lake than observed, which in
12 turn has a strong influence on local climate. Therefore, the HAR10 data points over water
13 surfaces were not included for hydrological modeling purposes.

14 The HAR10 precipitation output was compared to rain-gauge data and to Tropical Rainfall
15 Measuring Mission (TRMM) satellite precipitation estimates by Maussion et al. (2014). They
16 concluded that HAR10 accuracy in comparison to rain gauges was slightly less than TRMM;
17 however, orographic precipitation patterns and snowfall were more realistically simulated by
18 the WRF model. HAR10 temperatures in the summer months are closer to ground
19 observations than in winter (Maussion, 2014). Despite the winter cold bias, the overall
20 seasonality is well reproduced (Maussion, 2014). The cold bias effect on the accuracy of the
21 hydrologic-modeling results is assumed to be low, because hydrological processes governing
22 lake-level changes are more critical during the other three seasons of the year.

23 Lake-surface water temperature (LSWT) estimates from the ARC-Lake v2.0 data products
24 (MacCallum and Merchant, 2012) served as additional input for the hydrological modeling in
25 the Nam Co and Tangra Yumco basins. ARC-Lake v2.0 data products contain daytime and
26 nighttime LSWT observations from the series of (advanced) along-track scanning radiometers
27 for the period 1991-2011. Daytime and nighttime MODIS land-surface temperature (LST) 8-
28 day data at 1-km spatial resolution (MOD11A2) were averaged after plausibility check to
29 obtain mean daily LSWT time series for the Paiku Co and Mapam Yumco, where no ARC-
30 Lake v2.0 data were available.

31 Shuttle Radar Topography Mission (SRTM) 90-m digital elevation model (DEM) data (Farr
32 et al., 2007) were retrieved from the Consortium for Spatial Information (CGAIR-CSI)

1 Geoportal (<http://srtm.csi.cgiar.org>). We used the SRTM Version 4 data for derivations of
2 catchment-related information such as catchment boundary, river network, flow accumulation
3 and flow direction, as well as terrain attributes (slope and aspect).

4 For the Nam Co and Tangra Yumco basins, land-cover classifications were generated using
5 Landsat TM/ETM+ satellite imagery. The land-cover classifications consist of five classes
6 used for this analysis: water, wetland, grassland, barren land and glacier. For the Paiku Co
7 and Mapam Yumco basin, land-cover information could be obtained from the “Himalaya
8 Regional Land Cover” data base (http://www.glcn.org/databases/hima_landcover_en.jsp). The
9 Himalaya land-cover map was produced as part of the ‘Global Land Cover Network -
10 Regional Harmonization Program’, an initiative to compile land-cover information for the
11 Hindu Kush-Karakorum-Himalaya mountain range using a combination of visual and
12 automatic interpretation of recent Landsat ETM+ data. The land-cover classes were
13 reclassified according to the five classes mentioned above. Classes with similar characteristics
14 (e.g., vegetation type, degree of vegetation cover) were consolidated into a single class.

15 Lake-level observations from 2006 to 2010 for the Nam Co were provided by the Institute of
16 Tibetan Plateau Research (ITP), Chinese Academy of Sciences (CAS) and used for model
17 validation. However, lake-level values during the freezing (wintertime) periods are missing,
18 because the lake-level gauge was destroyed by lake ice, and therefore, rendered inoperable
19 each winter. Thus, data is only available for the ice-free period (May/June –
20 November/December). Unfortunately, the lake-level observation data contain an unknown
21 shift between the consecutive years.

22 Due to the absence of continuous lake-level measurements, we obtained satellite-based lake-
23 level and water-volume data for the four studied basins from the HydroWeb data base
24 (<http://www.legos.obs-mip.fr/en/soa/hydrologie/hydroweb/>) provided by LEGOS/OHS
25 (Laboratoire d'Etudes en Geodesie et Oceanographie Spatiales (LEGOS) from the
26 Oceanographie, et Hydrologie Spatiales (OHS)) (Crétaux et al., 2011). LEGOS lake-level and
27 water-volume data for the lakes included in this study were available for different time spans
28 (see Table 2). The start and end date of each time series were taken from the same season (as
29 far as available) in order to make lake levels or volumes comparable. Water-volume data
30 calculated through a combination of satellite images (e.g., MODIS, Landsat) and various
31 altimetric height level data (e.g., Topex/Poseidon, Jason-1) (Crétaux et al., 2011) were used
32 for model calibration (see Sect. 3.3). The mean annual lake-level changes derived from

1 LEGOS data for the Nam Co, Tangra Yumco, Paiku Co and Mapam Yumco (0.25, 0.26, -
2 0.07, -0.05 m yr⁻¹) are close to the change rates estimated by Zhang et al. (2011) (0.22, 0.25, -
3 0.04, -0.02 m yr⁻¹) and Phan et al. (2012) (0.23, 0.29, -0.12, -0.04 m yr⁻¹) using GLAS/ICESat
4 data (2003-2009) (Table 4, lower part).

5 MODIS snow-cover 8-day data of Terra (MOD10A2) and Aqua (MYD10A2) satellites at a
6 spatial resolution of 500 m served for validation of the snow modeling. As proposed in the
7 literature (e.g., Parajka and Blöschl, 2008; Gao et al., 2010; Zhang et al., 2012), we combined
8 Terra and Aqua data on a pixel basis to reduce cloud-contaminated pixels. The cloud pixels in
9 the Terra images were replaced by the corresponding Aqua pixel. For the period of time
10 before the Aqua satellite was launched (May, 2002), this combination procedure was not
11 possible, and we used the original MODIS/Terra snow-cover data. After the combination
12 procedure the cloud cover percentage was on average less than 1-2 % for all basins.

13

14 **3 Methods**

15 **3.1 Hydrological model concept and implementation**

16 The challenge for hydrological modelers is to balance the wish to adequately represent
17 complex processes with the need to simplify models for regions with limited data availability
18 (Wagener and Kollat, 2007). Therefore, we selected a semi-distributed conceptual model
19 structure, primarily following the J2000g model (Krause and Hanisch, 2009). The J2000g
20 model is a simplified version of the fully-distributed J2000 model (Krause, 2002). The main
21 differences with J2000 are that complex process descriptions (e.g., soil-water dynamics) are
22 simplified leading to a reduced number of land-surface and calibration parameters in the
23 J2000g model, and lateral flow processes between spatial model units and streamflow routing
24 are not accounted for by the J2000g model. The J2000g was successfully applied for
25 hydrological predictions in data-scarce basins (e.g., Deus et al., 2013; Knoche et al., 2014;
26 Rödiger et al., 2014; Pohl et al., 2015), including a previous modeling study in the Nam Co
27 basin (Krause et al., 2010).

28 The conceptual model presented here was realized within the Jena Adaptable Modelling
29 System (JAMS) framework (<http://jams.uni-jena.de/>). An overview of JAMS, especially the
30 JAMS software architecture and common structure of JAMS models is given in Kralisch and
31 Fischer (2012). Primarily, JAMS was developed as a JAVA-based framework for the

1 implementation of model components of the J2000 model. During recent years, a solid library
2 of single easily-manageable components has been developed by implementing a wide range
3 of existent hydrological-process concepts as encapsulated process modules and developing
4 new model modules, as needed. Due to the modular structure, the J2000g model could be
5 easily adapted and extended according to the specific characteristics of endorheic lake basins
6 in the TP region.

7 Meteorological data requirements for this study were daily times series of precipitation,
8 minimum, maximum and average air temperature, solar radiation, wind speed, relative
9 humidity and cloud fraction obtained from daily HAR10 data. Daily LSWT data served as
10 additional input for the calculation of the long-wave radiation term over the lake surface.
11 Process simulations were grouped into the following categories: i) lake, ii) land (non-
12 glacierized) and iii) glacier. A schematic illustration of the model structure and a detailed
13 description of the model components are given in the Supplement.

14 In brief, we used the regionalization procedure implemented in J2000g for the interpolation of
15 the HAR10 raster points (centroid of the raster cell) to each HRU unit. This combines Inverse
16 Distance Weighting (IDW) with an optional elevation correction. Net radiation was calculated
17 following the Food and Agriculture Organization of the United Nations (FAO) proposed use
18 of the Penman-Monteith model (Allen et al., 1998). We adapted the long-wave radiation part
19 of the FAO56 calculation to the special high altitude conditions on the TP, according to the
20 recommendations of Yin et al. (2008), and implemented the commonly used approach for
21 calculating net long-wave radiation over water surface (e.g., Jensen, 2010).

22 Potential evapotranspiration (PET) from land and snow surfaces (sublimation) is calculated
23 based on Penman-Monteith (Allen et al., 1998). For the estimation of open-water evaporation
24 rates from large lakes, we modified the Penman equation through the addition of an empirical
25 estimation of the lake heat storage (Jensen et al., 2005). As suggested by Valiantzas (2006),
26 we used the reduced wind function proposed by Linacre (1993) for the estimation of
27 evaporation from large open-water body surfaces.

28 The simple degree-day snow modeling approach of the standard J2000g model version was
29 replaced by the J2000 snow module that combines empirical or conceptual approaches with
30 more physically-based routines. This module takes into account the phases of snow
31 accumulation and the compaction of the snow pack caused by snowmelt or rain on the snow

1 pack. For a detailed description see Nepal et al. (2014). The glacier module calculates ice-
2 melt according to an extended temperature-index approach (Hock, 1999).

3 Soil-water budget and runoff processes are simulated using a simple water storage approach
4 (Krause and Hanisch, 2009). The storage capacity is defined from the field capacity of the
5 specific soil type within the respective modeling unit. Actual evapotranspiration (AET) is
6 calculated depending on the saturation of the soil-water storage, PET and a calibration
7 parameter. The J2000g model generates runoff only when the soil-water storage is saturated.
8 The partition into surface runoff and percolation depends on the slope and the maximum
9 percolation rate of the respective modeling unit which can be adapted by a calibration
10 parameter. The percolation component is transferred to the ground-water storage component.
11 The ground-water module calculates base flow using a linear outflow routine and a recession
12 parameter (Krause and Hanisch, 2009).

13 The lake module calculates the net evaporation (lake evaporation minus precipitation over the
14 lake's surface area). The lake-water storage change is the sum of i) direct runoff and base
15 flow from each modeling unit of the non-glacierized areas, and ii) glacier runoff (snow and
16 ice melt, and rainfall over glaciers) from each glacier HRU minus lake net evaporation. For
17 simplicity, the terms land runoff, glacier runoff and net evaporation are used to refer to
18 several water-balance components. Because the J2000g model does not account for water
19 routing and thus time delay of the discharge, the model is not fully suited to provide
20 continuous and precise estimates of lake-water storage changes.

21 **3.2 Delineation of spatial model entities**

22 In order to provide spatially-distributed information of landscape characteristics for the
23 hydrological modeling, we applied the Hydrological Response Units (HRUs) approach
24 (Flügel, 1995). Using ArcGIS software, HRUs with similar hydrological behaviour were
25 delineated by overlaying topographic-related and land-cover information. Soil and hydro-
26 geology information were not included in the overlay analysis, due to a lack of detailed data.
27 The distribution concept applied represents the landscape heterogeneity with a higher spatial
28 resolution in the complex high mountain areas (a large number of small polygons) than in the
29 relatively flat terrains in the lower elevations (smaller number of large polygons). The total
30 number of HRUs varies between 1928 (Paiku Co) and 8058 (Nam Co).

1 **3.3 Model-parameter estimation and model evaluation**

2 The J2000g model requires the definition of spatially-distributed land-surface parameters
3 describing the heterogenic land surface and the estimation of calibration parameters. Land-
4 surface parameters were derived from field studies or literature values. The field capacity was
5 derived as function of the soil types obtained from own field surveys. Due to the limited
6 availability of soil information for the TP, soil parameters were distributed according to
7 different land-cover and slope classes (Table 3).

8 Parameter-optimization procedures are difficult to apply in data-scarce regions such as the TP
9 (e.g., Winsemius et al., 2009). Moreover, various parameter set combinations may yield
10 equally acceptable representation of the (often limited) calibration data, which is referred to as
11 the equifinality problem (e.g., Beven, 2001; Beven and Freer, 2001). Due to a lack of
12 calibration data, we used default settings or parameter values given in the literature (see Table
13 S1 in the Supplement).

14 Following Mölg et al. (2014), we implemented a precipitation-scaling factor as additional
15 model parameter to account for i) HAR10 precipitation overestimation related to atmospheric-
16 model errors and/or ii) sublimation of blowing or drifting snow which was neglected in the
17 model. Due to the high uncertainty of the range of the precipitation-scaling factor in various
18 regions of the TP (Huintjes, 2014; Mölg et al., 2014; Pohl et al., 2015), we performed model
19 runs with precipitation-scaling factors varying between 0.3 and 1.0 with a 0.05 increment.
20 Because the precipitation-scaling factor was judged to be the parameter that contributes the
21 most to uncertainties in model results, all other climate forcing variables and model
22 parameters were held constant. We compared simulated mean annual lake-volume changes of
23 each model run with water-volume changes derived from remote-sensing data (Fig. 2). The
24 dotted line in Fig. 2 indicates the lake-volume changes derived from LEGOS data (see Table
25 2). The model run with the minimum difference between modeled and satellite-derived lake-
26 volume change was defined as reference run and thereby was used for an assessment of model
27 results. The “best” match between simulated and satellite-derived lake-volume change was
28 achieved by applying following precipitation-scaling factors: 0.80 (Nam Co), 0.75 (Tangra
29 Yumco), 0.85 (Paiku Co) and 0.50 (Mapam Yumco). We discuss the possible reasons for the
30 lower parameter value for the Mapam Yumco basin in Sect. 5.2.

31 Similar to the calibration process, data scarcity limited the establishment of rigorous and
32 systematic validation tests. Because water-level measurements from Nam Co provide

1 consistent time series between the months of June through November for the years 2006-
2 2010, we chose this period for validation. Given the fact that water routing is not considered
3 in the model, we compared mean monthly, instead of daily, water-level simulations and
4 measurements. For the calculation of monthly-average lake levels, the lake-level value of the
5 1st of June was set to zero in each year and the subsequent values were adjusted accordingly
6 to make the lake-level changes during the June-November period of the years 2006-2010
7 comparable.

8 For an independent assessment of the snow model capabilities, we compared modeled snow-
9 water equivalent (SWE) simulations with MODIS snow-cover data (see Sect. 2.2). Because
10 MODIS data provide no information about the amount of water stored as snow (i.e., SWE),
11 this comparison was only possible in an indirect way by comparing the percent or fraction of
12 snow-covered area (SCAF) derived from the model simulation and MODIS data. Any given
13 spatial model unit was considered as snow-covered at days when the amount of SWE was
14 larger than a specific threshold (i.e. 1, 10, 50 mm).

15

16 **4 Results**

17 Section 4.1 contains the comparison of simulated and measured water levels of the lake Nam
18 Co (Sect. 4.1.1) and of simulated snow cover dynamics with MODIS for all four study basins
19 (Sect. 4.1.2). Section 4.2 deals with the assessment of the modeling results regarding
20 spatiotemporal variations of water-balance components (Sect. 4.2.1) and their contributions to
21 each basin's water balance (Sect. 4.2.2) during the 2001-2010 period.

22 **4.1 Model evaluation**

23 **4.1.1 Comparison of simulated and measured water levels of the lake Nam Co**

24 Lake-level observations of Nam Co indicate a distinct seasonal dynamic with continuously
25 increasing lake levels during the months of June through September caused by runoff from
26 the non-glacierized land surface and glacier areas, a lake-level peak in September and
27 decreasing lake levels from October on primarily caused by lake evaporation. The overall
28 seasonal dynamic during the June-November period is well represented by the J2000g model
29 ($r = 0.81$) (Fig. 3). However, the model overestimates the lake level for the month of
30 November, except for the year 2006.

1 In general, the magnitude of the lake level evolution is less well simulated than its timing. The
2 comparison reveals a non-systematic pattern (Fig. 3). In 2006, the model is not able to
3 reproduce the observed increase in lake levels. The substantial lake-level rise of Nam Co in
4 2008 simulated by the model compares well with observed data. However, the lake-level
5 increase in 2009 is slightly overestimated. The absolute deviation between observed and
6 simulated relative changes of monthly-averaged lake levels during the June-November period
7 ranges between -0.31 m (2006) and 0.30 m (2009). The simulated relative lake-level change
8 during the June-November period averaged over the years 2006 to 2010 is 0.41 m, which is
9 approximately 0.05 m higher than the measured one (0.36 m).

10 **4.1.2 Comparison of the simulated snow-cover dynamics with MODIS**

11 The comparison of mean monthly values of modeled snow-covered area fraction (SCAF)
12 (SWE > 1 mm) and MODIS indicates that the model captures seasonal variability quite well.
13 However, there are large deviations in the magnitude. The modeled SCAF (SWE > 1mm) is
14 generally greater than the MODIS SCAF, with higher deviations in the Mapam Yumco and
15 Paiku Co basins (Nam Co: 30 % versus 22 %, Tangra Yumco: 17 % versus 8 %, Mapam
16 Yumco: 54 % versus 28 %, Paiku Co: 49 % versus 20 %, Fig. 4). During the winter months
17 November through April the overestimation by the model (up to a factor of 2) is generally
18 higher than during the summer season. During the months May through October, the modeled
19 SCAF (SWE > 1 mm) in the Nam Co and Tangra Yumco basins is even approximately 50 %
20 lower compared to MODIS. Figure 4 indicates how sensitive are the results by using different
21 thresholds for the amount of SWE to depict an area as snow-covered in the model. The use of
22 higher thresholds (SWE > 10, 50 mm) for derivations of SCAF from the model reduces the
23 overestimation, but also leads to an underestimation of the SCAF in early winter in most
24 basins (Fig. 4). A threshold larger than 10 mm seems to be not appropriate in order to derive
25 SCAF from the SWE simulations. It is more likely that the J2000g model overestimates
26 SCAF. This will be discussed later in Sect. 5.2.

27 **4.2 Comparative analysis of the four selected lake basins**

28 **4.2.1 Spatiotemporal patterns of hydrological components**

29 The percentage of the precipitation occurring during the wet season (June through September)
30 is more than half of the annual precipitation in all basins. Specifically, June-through-

1 September precipitation is approximately 80 % of the annual total in the Nam Co and Tangra
2 Yumco basins and around 60 % in the Paiku Co and Mapam Yumco basins (Fig. 5a). This
3 indicates a higher influence of the Westerlies in the Paiku Co and Mapam Yumco basins. As
4 simulated by the model, snow accumulation in the basins generally occurs beginning in mid-
5 September, reaching a first smaller peak between October and November and the maximum
6 peak between April and May, followed by rapid decrease in snow between May and June and
7 a slower rate of decrease until September. In the Mapam Yumco basin, simulated snowmelt
8 starts later and occurs over a shorter time period compared to the other basins (Fig. 5b). This
9 can be explained by lower air temperatures in this basin.

10 About 80 % of simulated annual terrestrial actual evapotranspiration (AET) occurs during the
11 growing season (May-October). Modeled AET has its maximum in July when the availability
12 of soil water and energy is highest. The seasonal cycle of modeled lake evaporation is
13 influenced by seasonal heat-storage changes in the lakes. The released heat in autumn acts as
14 energy source for evaporation. Thus, the evaporation is higher in autumn than in spring.

15 Approximately 70 % of annual precipitation is released to the atmosphere through AET and
16 does not contribute to the runoff in all basins. Discharge from non-glacierized land areas is
17 concentrated during the wet season (~80 % of annual runoff occurs during May through
18 October). Runoff starts to increase in spring with the beginning of snowmelt. The land runoff
19 peak in the Mapam Yumco basin occurs one month earlier (between June and July) compared
20 to the other basins (Fig. 5c), because of a higher contribution of snowmelt to the discharge.
21 Glacier runoff occurs during June through September in all basins (Fig. 5d), but with a later
22 beginning and a shorter duration of the melt season in the Mapam Yumco basin due to the
23 colder climate conditions.

24 Table 4 (upper part) summarizes annual means of modeled water-balance components for the
25 2001-2010 period for each basin. The annual mean of the model-simulated lake evaporation
26 rates varies between 700 and 900 mm yr⁻¹ for the four basins averaged over the 10-year study
27 period. Because of unlimited water availability, the modeled mean annual lake evaporation is
28 substantially higher than the land AET (see Table 4, upper part). Due to higher precipitation
29 amounts in the eastern part of the study region, the simulated mean annual AET is higher in
30 the east (~290 mm in the Nam Co basin) than in the west (~170 mm in the Mapam Yumco
31 basin) (Table 4, upper part).

1 Impacted by the decreasing precipitation gradient spatially from east to west, the model-
2 simulated mean annual land runoff in the Nam Co basin (~130 mm) is estimated to be more
3 than twice that in the Mapam Yumco basin (~60 mm) during the study period (Table 4, upper
4 part). The combination of various influencing variables such as local climate, topography,
5 land cover, soil and hydro-geological properties results in a spatially heterogeneous pattern of
6 runoff generation within the catchments. Figure 6 illustrates the altitudinal dependence of the
7 mean annual basin-wide precipitation total and runoff from glaciers and non-glacierized land
8 areas, as computed by the J2000g model. The area-altitude relation (hypsometry) for glacier
9 and non-glacierized areas is based on mean elevations of the respective model entities. Larger
10 precipitation amounts in the high mountainous and hilly headwater areas result in higher land
11 runoff estimates compared to lower elevation areas (Fig. 6). Indeed, the increase of land
12 runoff with altitude is higher than the elevation-dependent increase of precipitation. The non-
13 glacierized high-elevation areas characterized by sparse vegetation, poorly developed soils,
14 steep topography and lower air temperatures indicate smaller soil-water contents and lower
15 AET rates compared to lower elevation bands, resulting in higher runoff rates.

16 In all studied basins, the runoff from glacier areas located in lower elevations zones (<5750 m
17 a.s.l.) significantly exceeds the land runoff in the same elevation zones (Fig. 6), due to high
18 ice-melt rates in the ablation areas. Because of lower temperatures and higher snowfall rates
19 at higher elevations, the modeled glacier runoff decreases with altitude. The modeled mean
20 annual glacier runoff averaged over all glacier HRUs in the Nam Co and Tangra Yumco
21 basins (~1300 mm) is considerably higher than in the Paiku Co (~300 mm) and Mapam
22 Yumco (~600 mm) basins. This is judged to be caused by lower air temperatures (~2°C less)
23 in the glacier areas of the Paiku Co and Mapam Yumco basins.

24 **4.2.2 Contributions of the individual hydrological components to the water** 25 **balance**

26 Table 4 (lower part) summarizes the model-simulated mean annual lake-volume and level
27 changes and the contribution of non-glacierized land, glacier, and lake areas to the total water-
28 budget during the 2001-2010 study period. Comparative values for the mean annual lake-level
29 changes derived from remote-sensing data also are given in Table 4 (lower part). The
30 contribution of glacier runoff to the total basin runoff volume in the Nam Co (19 %), Tangra
31 Yumco (14 %) and Mapam Yumco (15 %) basins is relatively low compared to the runoff
32 contribution from non-glacierized land areas. The glacierization in the Paiku Co basin is about

1 two to five times larger than in the other three basins, but the glacier-melt contribution to the
2 total basin runoff volume is only around twice as high (30 %) due to lower glacier-melt rates.
3 Despite the generally higher glacier contribution in the Paiku Co, the water balance is slightly
4 negative during the study period (Table 4, lower part). The water loss for Paiku Co exceeds
5 the water gain by 10 %. In contrast, the total water inflow in the Tangra Yumco and Nam Co
6 basins exceeds the water loss by a factor of 1.4 or 1.5, respectively. In the Mapam Yumco
7 basin the water gain and loss terms tend to balance each other out (Table 4, lower part), based
8 upon the model simulation.

9 In order to better predict and understand the role of glaciers for the mean annual water
10 balance, a hypothetical scenario with ice-free conditions were evaluated through model
11 simulations for each lake basin. Therefore, the land-cover class of all glacier HRUs was
12 changed to barren land. In the absence of glaciers, the total runoff volumes in the Nam Co and
13 Tangra Yumco basins would be about 13 % lower than with ice-melt water contribution
14 during the 2001-2010 period (compared to the reference run). Thus, the mean annual lake-
15 level increases of Nam Co and Tangra Yumco would be reduced from 0.24 to 0.15 m and
16 from 0.29 to 0.17 m, respectively. In the Mapam Yumco and Paiku Co basins, the total runoff
17 volumes would decrease by approximately 30 % and the resulting mean annual lake-level
18 changes would change from 0.02 to -0.18 m and from -0.07 to -0.25 m, respectively, under
19 ice-free conditions. From this latter evaluation, it can be concluded that the mean annual net
20 water budget would noticeably change without ice-melt water contribution; however the
21 water balance in the Nam Co and Tangra Yumco remains positive.

22 Based upon the J2000g modeling results, the differences in the water balance among the four
23 studied lakes are primarily caused by relatively higher land runoff contributions in the Nam
24 Co and Tangra Yumco basins compared to the Paiku Co and Mapam Yumco basins. This is
25 related to relatively higher precipitation totals in the Nam Co and Tangra Yumco basins
26 compared to the other two basins during the 2001-2010 period.

27 Figure 7a-d (upper panels) illustrates the yearly water contribution in km³ of each land cover
28 type (land, glacier, and lake) for the 2001-2010 period. The annual percentage deviations
29 from the 10-year average of several hydrological system components are presented in Fig. 7a-
30 d (lower panels). Over the study period, annual relative lake-volume changes in the four
31 basins indicate similar patterns. A relatively high correlation of lake-volume changes is found
32 between the Nam Co and Tangra Yumco basin ($r = 0.82$). These are the basins with a higher

1 proportion of June-through-September precipitation compared to the Paiku Co and Mapam
2 Yumco basins.

3 The modeled annual lake-volume changes of all four lakes are highly correlated to inter-
4 annual variations of land runoff ($r \approx 0.99$). The year-to-year variability of runoff from non-
5 glacierized land surfaces, in turn, is strongly related to inter-annual variations of precipitation
6 ($r \approx 0.92$). Inter-annual variability of lake evaporation is low in all four studied basins and not
7 correlated to lake-level changes. Thus, lake evaporation seems to have a minor impact on
8 inter-annual lake-level variations during the study period. There is also no correlation
9 between annual glacier-melt amounts and lake-volume changes for the four basins. This
10 suggests that glacier-melt runoff is not the main driving force for inter-annual lake variations
11 during the last decade. Although the modeled annual glacier runoff is greater than the 10-year
12 average in the year 2006 in all basins, lower precipitation amounts lead to less land runoff,
13 causing a lake-volume decrease in this year in all basins. In contrast, the year 2008 is judged
14 as having anomalous conditions, with modeled precipitation and land runoff substantially
15 above average and with below-average glacier melt, resulting in a lake-volume increase in all
16 basins. Differences in annual lake-volume changes among the basins are caused principally
17 by regional differences in the inter-annual variations of precipitation.

18

19 **5 Discussion**

20 **5.1 Comparison with other studies**

21 **5.1.1 Estimation of the water-balance components**

22 Due to the scarcity of field measurements, model simulations of water-balance components
23 are limited in the TP region. Evaporation over lake surfaces has been estimated for only few
24 lakes on the TP, based on model simulations (e.g., Morrill, 2004; Haginoya et al., 2009; Xu et
25 al., 2009; Yu et al., 2011). Mean annual lake-evaporation estimates vary between 700 and
26 1200 mm. The lake-evaporation rates simulated with the J2000g model (between 710 and 910
27 mm yr^{-1}) are within this range (Table 4). There are only few studies for the TP for assessing
28 the actual evapotranspiration over alpine grassland, based on measurements and model
29 simulations (e.g., Gu et al., 2008; Yin et al., 2013; Zhu et al., 2014). Yin et al. (2013)
30 estimated AET over the entire TP using meteorological data available between 1981 and 2010

1 from 80 weather stations as model input for the Lund-Potsdam-Jena dynamic vegetation
2 model (Sitch et al., 2003). For the south-central TP, the simulated mean annual AET ranges
3 from 100 to 300 mm, with generally higher values in the east and lower values in the drier
4 regions in the west. Our simulated AET estimates for the four basins vary between 170 and
5 290 mm yr⁻¹, decreasing from east (Nam Co basin) to west (Mapam Yumco basin) (Table 4).
6 This compares favorably with the study reported by Yin et al. (2013).

7 Using a simplified procedure, Yin et al. (2013) developed spatial patterns of the surface-water
8 budget over the entire TP for the 1981-2010 period by estimating the difference between
9 precipitation and AET (P-AET). The results revealed that P-AET depends on climate regimes
10 and gradually decreases from the east (~150 mm yr⁻¹) to the west (~50 mm yr⁻¹) in the study
11 region. Our model simulations indicate quite similar runoff patterns compared to the findings
12 of Yin et al. (2013), with decreasing annual means from the east (~130 mm in the Nam Co
13 basin) to the west (~60 mm in the Mapam Yumco basin). The calculated AET/precipitation
14 ratio of around 0.7 in all basins agrees well with study results from Gu et al. (2008).

15 The mean annual glacier runoff of 1320 mm, simulated with the J2000g model for the Nam
16 Co basin, compares quite well with estimated glacier-melt quantities for the Zhadang glacier
17 in the Nam Co basin using more complex SEB/MB models (Mölg et al., 2014: 1375 mm yr⁻¹;
18 Huintjes et al., 2015: 1325 mm yr⁻¹).

19 **5.1.2 Factors controlling the water balance and lake-level variability**

20 Many studies emphasize the importance of glacier-meltwater contribution to the water budget
21 of Tibetan lakes (e.g., Zhu et al., 2010). However, only few studies have quantitatively
22 estimated glacier-meltwater contribution to total runoff in the TP region, due to the difficulty
23 to estimate glacier-volume changes (Li, B. et al., 2014). Li, B. et al. (2014) estimated a
24 glacier-runoff contribution of 15 % of the total runoff (during 2006-2011) in a sub-basin of
25 the Nam Co basin, the Qugaqie basin (8.4 % glacier coverage), using an energy-balance based
26 glacier-melt model and the 'Gridded Subsurface Hydrologic Analysis (GSSHA) model'
27 (Downer and Ogden, 2004). Based upon the J2000g model results, the glacier contribution
28 ranges between 14 and 30 % in the four studied basins (1-6 % glacier coverage) during the
29 2001-2010 period. This range of value is slightly higher than that computed by Li, B. et al.
30 (2014) considering the percentage of basin area covered by glaciers.

1 Simulated glacier-meltwater contribution is generally lower compared to the runoff
2 contribution from non-glacierized areas. However, glaciers make an important contribution to
3 the water budget during the 10-year period considering the small extent of ice-covered areas
4 in the four studied lake basins. Indeed, the water balance in the Nam Co and Tangra Yumco
5 basins would also be positive without ice-meltwater contribution during the study period,
6 based on the results of the ice-free scenarios [\(Sect. 4.2.2\)](#). Thus, the question arises why the
7 Nam Co and Tangra Yumco indicate a non-equilibrium state; whereas, Paiku Co and Mapam
8 Yumco are at a state close to the hydrologic equilibrium.

9 Endorheic lakes respond to climatic changes to maintain equilibrium between input and
10 output, and to reach steady state. Due to the time lag of lakes in responding to climatic
11 changes, this modeling study cannot confirm whether or not the shift towards a positive water
12 balance in the Nam Co and Tangra Yumco basins or the negative shift in the water balance of
13 the Paiku Co basin, respectively, was primarily caused by changes in precipitation, glacier
14 melt, evapotranspiration, etc. However, inter-annual lake-level variations are highly positively
15 correlated with precipitation and land runoff. This supports the assumption of other studies
16 (e.g., Lei et al., 2014; Li, Y. et al., 2014; Song et al., 2014) that increasing precipitation is the
17 primary factor causing lake-level increases in the central TP (where Nam Co and Tangra
18 Yumco are located). The relative stability or slight lake-level declines in the marginal region
19 of the TP (where Paiku Co and Mapam Yumco are located) seem to be related to relative
20 stable or slightly decreased precipitation (e.g., Lei et al., 2014). Both changes in large-scale
21 circulation systems and local circulation are assumed to be responsible for spatially varying
22 changes in moisture flux over the TP (e.g., Gao et al., 2014, 2015). However, these factors are
23 still under debate and further research is needed (Gao et al., 2015).

24 [The potential evaporation decreased in most areas on the TP during 1961-2000, primarily](#)
25 [caused by decreasing wind speeds \(Xie and Zhu, 2013\)](#). A decreasing trend in potential
26 evaporation before 2000 might have resulted in rising lake levels in the central TP. However,
27 this factor did not prevent the lake shrinkage along the south-west periphery of the TP,
28 indicating that lake evaporation is not a primary factor for explaining the spatial differences of
29 lake-level changes between the central and southern TP (Lei et al., 2014). In addition, Li, Y.
30 et al. (2014) argued that recent rapid lake expansion in the central TP cannot be explained by
31 changes in potential evaporation, because the overall increasing tendency of potential

1 evaporation in the TP region after 2000 (Yin et al., 2013; Li, Y. et al., 2014) would negate the
2 effect of increasing precipitation on lake levels.

3 Under the assumption that glacier-melt runoff increased during the last decades due to climate
4 warming, it is very likely that glacier-meltwater supply augmented the precipitation-driven
5 lake areal expansion in the central TP region (Song et al., 2014). In the Mapam Yumco and
6 Paiku Co basins, glacier-meltwater discharge might have mitigated lake-level declining and
7 acted as a regulating factor (Ye et al., 2008; Nie et al., 2012).

8 Li, Y. et al. (2014) suggest that spatial variations in lake-level changes might be related to
9 different distributions and types of permafrost. Most lakes in the central-northern TP with
10 continuous permafrost are rapidly expanding; whereas, lakes in the southern region with
11 isolated permafrost are relatively stable or slightly decreasing. Thus, accelerated permafrost
12 melting might have contributed to the rapid lake expansion in the central and northern TP
13 subregions (Li, Y. et al., 2014). The water contribution from permafrost will become limited
14 when ground temperature increases-remains above the melting point of the frozen soil and the
15 water held in the frozen soil has been released (Li, Y. et al., 2014). Li, Y. et al. (2014) suggest
16 that permafrost-meltwater contribution may have become already limited in the southern TP.
17 However, this is difficult to corroborate given the absence of observational data for the
18 studied lake basins. The questions remain i) how large is the volume of water released due to
19 thinning and thawing of permafrost, and ii) to what extent can it modulate basin runoff. These
20 cannot be answered without adequate information about permafrost occurrence, thickness and
21 ice content in the studied basins.

22 Differences in the response time or, in other words, the time required to reach an equilibrium
23 state could also be a reason for observed differences in lake-level changes. Based upon remote
24 sensing data, the lake area of Nam Co and Tangra Yumco expanded by 4.6 % and 1.8 %,
25 respectively, between 1970 and 2008 (Liao et al., 2013). The lakeshore slopes of Tangra
26 Yumco are steeper compared to the Nam Co. Steep-sided lakes have a longer equilibrium
27 response time, because of a lower rate of change of the lake area with volume (Mason, 1994).
28 Based upon paleo-shorelines, the post-glacial lake-level high of the Nam Co and Tangra
29 Yumco was about 29 m (Schütt et al., 2008) and 185 m (Rades et al., 2013), respectively,
30 above the present-day lake level, supporting the assumption that the Nam Co has a shorter
31 response time to compensate for the increment in net inflow (i.e. faster and stronger reaction

1 of its lake area). Moreover, the water supply coefficient (basin area/lake area ratio) for the
2 Nam Co is smaller than for the Tangra Yumco basin (5.5 versus 11.0).

3 The lake extent of Paiku Co and Mapam Yumco decreased by 3.7 and 0.8 %, respectively,
4 between 1970 and 2008 (Liao et al., 2013). The lakeshores of Mapam Yumco are generally
5 flatter compared to the Paiku Co. However, due to only small lake-area variations of Mapam
6 Yumco during the last decades (Liao et al., 2013), differences in lake morphology seem not to
7 be the reason for the relative stability of the recent water levels of Mapam Yumco.
8 Differences in the water-supply coefficient of the Paiku Co and Mapam Yumco basin are
9 quite low (8.8 versus 10.6).

10 Based upon results of other studies in the region (e.g., Lei et al., 2013), the effects of
11 upwelling and downwelling groundwater related to fault zones and lake-groundwater
12 exchanges on the water balance were assumed to be negligible. However, Zhou et al. (2013)
13 suggest that water leakage related to seepage might play an essential role in the hydrological
14 cycle of the TP, due to the large numbers of lakes and the sub-surface fault system in the TP
15 region. Groundwater outflow from the Mapam Yumco to the Langa Co (located only a few
16 kilometers to the west about 15 m below the Mapam Yumco) cannot be excluded and could
17 be a reason for the relatively stable water levels of Mapam Yumco. In the more recent past,
18 the Mapam Yumco and the Langa Co were connected by the natural river Ganga Chu having
19 an extent about 10 km. However, currently there is no surface outflow (Liao et al., 2013).

20 **5.2 Limitations and uncertainties**

21 Hydrological modeling is hindered by systematic or random model-input errors, model-
22 parameter uncertainty and model-structure inadequacies (Sivapalan, 2003). As stated in many
23 studies (e.g., Knoche et al., 2014; Pohl et al., 2015), precipitation input is the primary source
24 of uncertainty in hydrological modeling studies in data-scarce regions. HAR10 data has been
25 successfully used as modeling input in various studies (Huintjes, 2014, Mölg et al., 2014;
26 Huintjes et al., 2015; Pohl et al., 2015). However, these studies also needed to apply a
27 precipitation-scaling factor < 1 . Maussion et al. (2014) could not find a systematic bias in
28 comparison with station observations, but it is probable that overestimation of precipitation
29 amounts occurs at high altitudes.

30 The precipitation-scaling factors were kept constant for the entire 10-year period, because
31 there is no opportunity to derive varying scaling factors for individual years, due to a lack of

1 observations in the lake basins included in this study. This may have an impact on inter-
2 annual variations of modeling results. The non-systematic deviations between simulated and
3 measured lake levels of the Nam Co (Fig. 3) might be related to a non-systematic error pattern
4 in the HAR10 precipitation data. The primary issue is that HAR10 precipitation cannot be
5 validated to a sufficient degree, because available data are for stations that are located at
6 lower elevations, and no accuracy assessment can be done for the higher elevation zones
7 where study basins are located. The comparison with available station data suggests that the
8 accuracy of the precipitation data is probably regionally dependent (Maussion et al., 2014).
9 This makes it difficult to find a fixed precipitation-scaling factor that is applicable for
10 different regions of the TP.

11 As described in Sect. 3.3, we conducted multiple model runs using precipitation-scaling
12 factors between 0.3 and 1.0, seeking a precipitation-scaling factor that best simulates satellite-
13 derived lake-volume changes. There may be errors in the satellite-derived water-volume data,
14 which in turn might have affected the estimation of the precipitation-scaling factor and
15 thereby the accuracy of model results. However, the precipitation-scaling factors obtained for
16 the Nam Co (0.80), Tangra Yumco (0.75) and Paiku Co (0.85) basins are relatively close to
17 the scaling factor used for the Zhadang glacier in the Nam Co basin in the study of Mölg et al.
18 (2014). They found very good agreement between glacier mass-balance model calculations
19 and available in-situ measurements by applying a precipitation-scaling factor of 0.79. This
20 gives us confidence that the scaling factors used in our study seemed to be within an
21 acceptable range.

22 The relatively low precipitation-scaling factor of 0.50 obtained for the Mapam Yumco basin
23 seems to be plausible when comparing HAR10 precipitation with weather station data of
24 Burang (30°17'N, 81°15'E, ~30 km to the south, closest station with available data) published
25 in Liao et al. (2013). The mean annual precipitation total of Burang is 150 mm yr⁻¹ for the
26 period 2001-2009; whereas, the nearest HAR10 point gives a mean annual precipitation
27 amount of 330 mm yr⁻¹. Huintjes (2014) also found that a reduction of the precipitation by
28 more than 50 % leads to more reliable mass-balance results for the Naimona'nyi glacier
29 (Gurla Mandhata, south western TP) which is located close to the Mapam Yumco basin.

30 Uncertainty arises also from the fact that the precipitation-scaling factor can compensate for
31 not only input data errors but also model-structure inadequacies. Blowing-snow sublimation
32 was neglected in our modeling approach, due to the complexity of this process in complex

1 terrain (Vionnet et al. 2014). However, wind-induced sublimation of suspended snow above
2 the snow pack can be a significant water loss to the atmosphere (e.g., Bowling et al., 2004;
3 Strasser et al., 2008; Vionnet et al., 2014). Vionnet et al. (2014) simulated total sublimation
4 (surface + blowing snow) in alpine terrain (French Alps) using a fully coupled
5 snowpack/atmosphere model. They estimated that blowing-snow sublimation is two thirds of
6 total sublimation. This process is judged to be important in the study area, due to the
7 relatively dry near-surface conditions and relatively higher wind speeds occurring during the
8 winter months. Thus, the low values of scaling factor applied in the Mapam Yumco basin
9 (0.5) and in the study of Pohl et al. (2015) (0.37) might be an indication that drifting-snow
10 sublimation plays a greater role in regions which are stronger influenced by Westerlies.

11 The omission of processes such as snow redistribution by wind and avalanches and snow loss
12 by blowing-snow sublimation may affect snow-cover patterns as well as the magnitude and
13 timing of melt runoff (Pellicciotti et al., 2014). This could also be a reason for the larger areal
14 snow-cover extent in the model simulation during the winter season compared to MODIS
15 (Sect. 4.1.2). Explanations for lower SCAF values of the model during the summer period
16 could be related to the fact that the MODIS/Terra data are collected only in the morning
17 (10:30 AM) rather than at several times during the day. That means that MODIS indicates
18 snow cover at days when snow was accumulated during the previous night or early morning
19 but which might be sublimated or melted later during the day (Kropacek et al., 2010).

20 Given the limited data availability, further assumptions and simplifications in the model were
21 required. The currently implemented glacier-melt model component according to Hock
22 (1999) is a simple, robust and easy to use methodology that does not account for the
23 transformation of snow into ice. Thus, simulated snowmelt amounts on glacier surfaces might
24 be overestimated. Because glacier-volume changes are not considered in J2000g, unrealistic
25 amounts of glacier-meltwater could be generated. However, the impact of this effect on model
26 results is assumed to be small over the 10-year period. The consideration of glacier-volume
27 changes would be of higher importance for long-term model simulations.

28 Effects of lake-groundwater interactions were neglected in the model, because the
29 quantification of flow between aquifer systems and a deep lake is difficult (Rosenberry et al.,
30 2014). However, it is unclear if and to what extent intermittent (at irregular time intervals)
31 exfiltration and infiltration processes might occur, thereby impacting water-level fluctuations.
32 The stated values of lake-groundwater exchange rates do strongly vary within literature by

1 more than five orders of magnitude (Rosenberry et al., 2014). The lack of consideration of
2 lake-groundwater interactions could be the reason that the observed lake-level decrease of the
3 Nam Co during the months of October and November is not well represented by the model. If
4 lake levels rise higher than adjacent ground-water levels, lake water may move into the
5 adjacent lakeshores' subsurface. This additional storage factor would basically have a
6 dampening effect on lake-level dynamics. However, in view of multi-annual lake changes,
7 lake-groundwater exchanges are assumed to be negligible.

8

9 **6 Conclusions and outlook**

10 Hydrological modeling is required to allow for a quantitative assessment of differences in the
11 water balance and thus a better understanding of the factors affecting water balance in the TP
12 region. Addressing this research need, we developed a modeling framework integrating
13 atmospheric-model output and satellite-based data, and applied it to four selected endorheic
14 lakes across the southern-central part of the TP. The hydrological model J2000g was adapted
15 to the specific characteristics of endorheic lake basins in the TP region. The model-derived
16 atmospheric data HAR10 and satellite-derived lake-water surface temperature ([Sect. 2.2](#))
17 served as input for the modeling period 2001-2010. Due to missing continuous lake-level in-
18 situ data, we used satellite-derived lake-volume changes as a model-performance criterion.

19 The adapted J2000g model version reasonably captured seasonal dynamics of relevant
20 hydrological processes. Water-balance estimates of individual years should be ~~considered~~
21 [carefully interpreted with care](#), due to possible unsystematic error patterns in HAR10
22 precipitation. Nevertheless, uncertainties which appear to be related to the precipitation-
23 scaling factor, should not affect the overall conclusions drawn from the model-application
24 results, [as discussed in Sect. 5.2](#).

25 The major outcomes can be summarized as follows:

- 26 • The seasonal hydrological dynamics and spatial variations of runoff generation within
27 the basins are similar for all lake basins; however, the several water-balance
28 components vary quantitatively among the four basins.
- 29 • Differences in the mean annual water balances among the four basins are primarily
30 related to higher precipitation totals and attributed runoff generation in the basins with
31 a higher monsoon influence (Nam Co and Tangra Yumco).

- 1 • The glacier-meltwater contribution to the total basin runoff volume (between 14 and
2 30 % averaged over the 10-year period) plays a less important role compared to runoff
3 generation from rainfall and snowmelt on non-glacierized land areas. However,
4 considering the small part of glacier areas in the study basins (1-6 %), glaciers make
5 an important contribution to the water balance.
- 6 • Based upon hypothetical ice-free scenarios in the hydrological model, ice-melt water
7 constitutes an important water-supply component for basins with lower precipitation
8 (Mapam Yumco and Paiku Co), in order to maintain a state close to equilibrium;
9 whereas, the water balance in the basins with higher precipitation (Nam Co and Tangra
10 Yumco) would be still positive under ice-free conditions.
- 11 • Precipitation and associated runoff are the main driving forces for inter-annual lake-
12 level variations during the 2001-2010 period. Both are highly positively correlated
13 with annual lake-level changes, whereas no correlation is found between inter-annual
14 variability of lake levels and glacier runoff or lake evaporation.

15 For the 10-year modeling period used in this study, it is not possible to draw definitive
16 conclusions about the hydrological changes that might have led to imbalances in the water
17 budgets of the four studied lakes. However, the model results support the assumption of other
18 studies that contrasting patterns in lake-level fluctuations across the TP are closely linked to
19 spatial differences in precipitation.

20 This study demonstrates the feasibility of a methodological approach combining distributed
21 hydrological modeling with atmospheric-model output and various satellite-based data to
22 overcome the data-scarcity problem in the TP region. The integration of readily available
23 model-derived atmospheric and remote-sensing data with hydrological modeling has the
24 potential to improve our understanding of spatiotemporal hydrological patterns and to
25 quantify water-balance components, even in ungauged or poorly gauged basins. The modeling
26 framework presented in this study provides a useful basis for future regionally focused
27 investigations on the space-time transition of lake changes in the TP region.

28 Model applications in such a data-scarce region have inherent uncertainty which should be
29 perceived as useful information rather than a lack of basic knowledge or understanding
30 (Blöschl and Montanari, 2010). An uncertainty and sensitivity analysis that includes the
31 assessment of spatially and temporally variable effects on model outputs will allow specific
32 and detailed recommendations on the timing and locations of future field measurements (e.g.,

1 Ragetti et al., 2013). There is an urgent need in such studies for meteorological observations
2 (particularly precipitation in high mountain regions) and monitoring of land-surface
3 characteristics (vegetation, soil and hydrogeological properties), in order to reduce the model
4 uncertainties arising from input data and land-surface parameterization.

5 Overall, future research should focus on model-independent data describing hydrological
6 system components which can be used for multi-response calibration and validation purposes.
7 Water-level and volume estimations with a higher temporal resolution are expected to be
8 produced from new satellite-altimetry data, such as from Cryosat (continuously data available
9 since 2012, planed until 2017), Sentinel-3 (2015) and Jason-CS (2017) (Kleinherenbrink et
10 al., 2015), which could be used as calibration or validation data in further model applications
11 in the future.

12

13 **Author contribution**

14 S.B. designed the study, extended the J2000g model, performed modeling studies, analyzed
15 data and wrote the main paper and the supplementary information. F.M. developed HAR and
16 analyzed HAR data. P.K. developed original J2000g and helped to enhance the model. F.M.
17 and M.F. participated in field work. M.F. carried out soil analysis. All authors continuously
18 discussed the results and developed the analysis further. F.M., M.F. and P.K. commented on
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20

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31

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2 factors from 1971 to 2004 in the Nam Co basin of the Tibetan Plateau, Chinese Sci. Bull., 55,
3 1294–1303, 2010.

4

1 Table 1. Basic information of selected basins in the study region. Data sources are described
 2 in Sect. 2.2.

Lake name	Elev. (m a.s.l.)	Lake center		Basin area (km ²)	Lake area (km ²)	Land cover (%)				
		Lat	Long			Lake	Glacier	Grassland	Wetland	Barren land
Nam Co	4725	30°42'	90°33'	10760	1950	18	2	39	8	33
Tangra Yumco	4540	31°00'	86°34'	9010	830	9	0.96	31	0.4	59
Paiku Co	4585	28°55'	85°35'	2380	270	10	6.5	43	0.5	40
Mapam Yumco	4580	30°42'	81°28'	4440	420	10	1.5	64	2.5	22

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1 Table 2. Lake-level and water-volume changes derived from LEGOS data for the four studied
 2 lakes.

Lake name	Start date	Start volume (km ³)	Start level (m)	End date	End volume (km ³)	End level (m)	Δ Lake volume (km ³ yr ⁻¹)	Δ Lake level (m yr ⁻¹)
Nam Co	27/09/2001	1.3	4722.683	01/10/2010	5.3	4724.697	0.44	0.22
Tangra Yumco	07/10/2001	0	4533.997	25/10/2009	1.7	4535.987	0.21	0.25
Paiku Co	02/06/2004	0	4578.067	04/03/2008	-0.08	4577.768	-0.02	-0.07
Mapam Yumco	30/10/2003	0.02	4585.551	21/11/2009	-0.1	4585.231	-0.01	-0.05

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1 Table 3. Soil parameters used as input for the hydrological modeling.

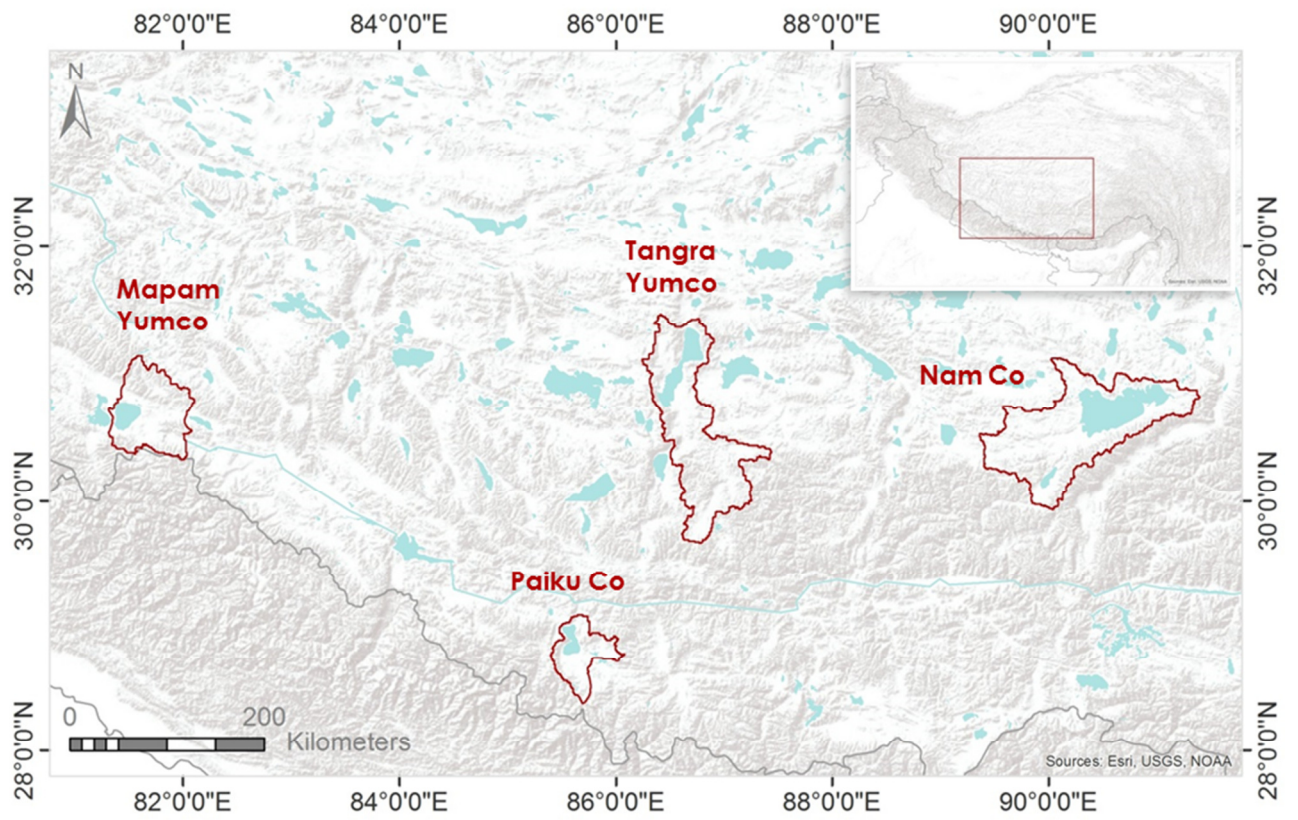
Combination land cover – slope	Soil depth [cm]	Field capacity							
		Total [mm]	0-1 dm [mm/dm]	1-2 dm [mm/dm]	2-3 dm [mm/dm]	3-4 dm [mm/dm]	4-5 dm [mm/dm]	5-6 dm [mm/dm]	6-7 dm [mm/dm]
wetland	70	236	60	60	60	14	14	14	14
grassland <15°	70	120	18	18	18	18	16	16	16
grassland >15°	40	68	18	18	16	16	-	-	-
barren land <5°	20	14	7	7	-	-	-	-	-
barren land >5°	10	7	7	-	-	-	-	-	-

2

1 Table 4. Mean annual water-balance components, water-budget and lake-level changes for the
 2 four studied lake basins for the study period 2001-2010 derived from the reference run. The
 3 variation ranges of the mean annual water-balance components correspond to model runs with
 4 precipitation-scaling factors ± 0.05 .

	Western basin			→	Eastern basin
	Mapam Yumco	Paiku Co	Tangra Yumco		Nam Co
Water-balance components [mm yr⁻¹]					
<u>Land</u>					
Precipitation	230 (± 24)	250 (± 15)	300 (± 20)		420 (± 27)
AET	170 (± 9)	180 (± 5)	210 (± 7)		290 (± 8)
Land runoff	60 (± 14)	70 (± 8)	90 (± 12)		130 (± 18)
<u>Glacier</u>					
Precipitation	330 (± 33)	480 (± 28)	330 (± 22)		560 (± 35)
Glacier runoff	600 (± 8)	320 (± 4)	1320 (± 12)		1320 (± 4)
<u>Lake</u>					
On-lake precipitation	90 (± 9)	140 (± 8)	150 (± 10)		290 (± 18)
Lake evaporation	710 (-)	910 (-)	840 (-)		770 (-)
Net evaporation	620 (± 9)	770 (± 8)	690 (± 10)		580 (± 18)
Water-budget [km³ yr⁻¹]					
<u>Water gain</u>					
Land runoff (% of total basin runoff)	0.23 (85)	0.14 (70)	0.70 (86)		1.15 (81)
Glacier runoff (% of total basin runoff)	0.04 (15)	0.06 (30)	0.11 (14)		0.27 (19)
<u>Water loss</u>					
Net evaporation	-0.26	-0.22	-0.57		-0.95
<u>Net water-budget</u>					
Lake-volume change	0.01	-0.02	0.24		0.47
Lake-level [m yr⁻¹]					
Simulated	0.02	-0.07	0.29		0.24
Zhang et al. (2011) (GLAS/ICESat 2003-2009)	-0.02	-0.04	0.26		0.25
Phan et al. (2012) (GLAS/ICESat 2003-2009)	-0.043	-0.118	0.291		0.230
LEGOS*	-0.05	-0.07	0.25		0.22

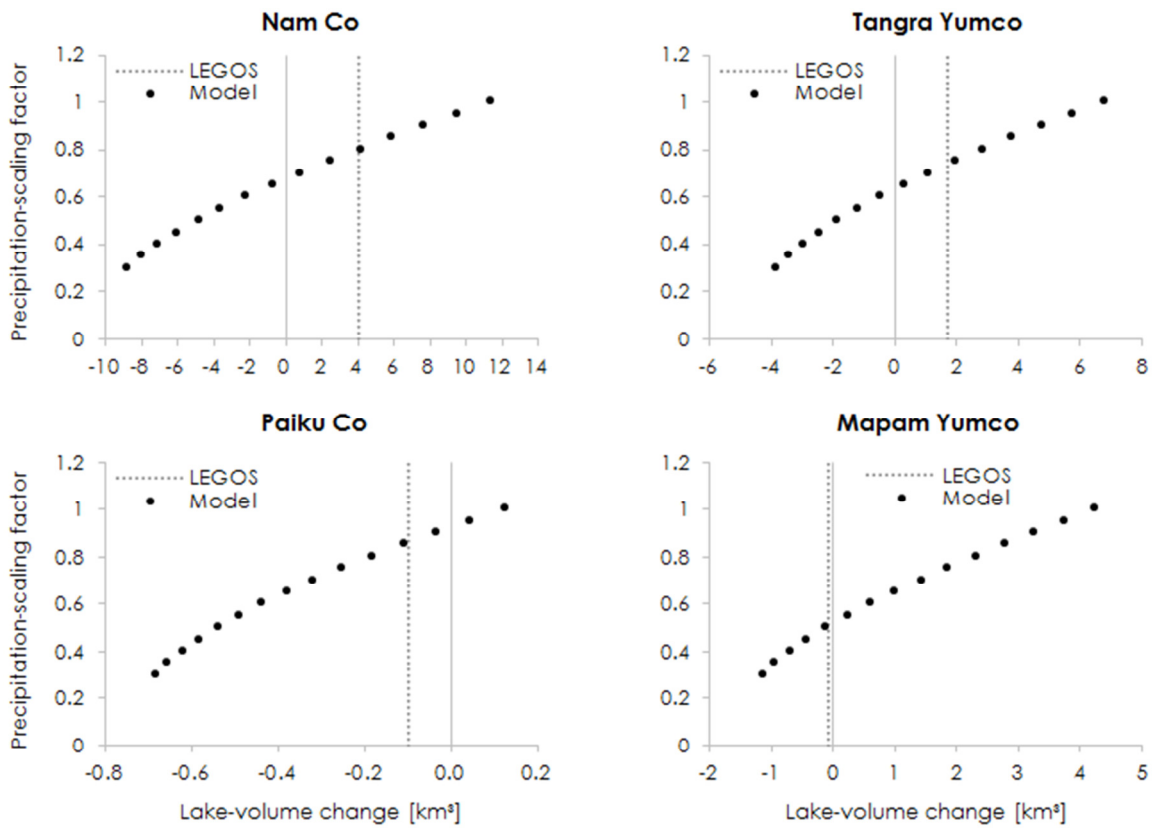
5 *Mean annual lake-level rates for the studied basins correspond to following time periods: Nam Co – 2001-2010; Tangra Yumco
 6 – 2001-2009; Paiku Co – 2004-2008; Mapam Yumco – 2003-2009.



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2 Figure 1. Location of the study region comprising four selected endorheic lake basins.

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2 Figure 2. Model-simulated lake-volume changes for Nam Co, Tangra Yumo, Paiku Co and
 3 Mapam Yumco for the time periods given in Table 2 using precipitation-scaling factors
 4 varying between 0.3 and 1.0. Dotted line indicates lake-volume changes derived from remote
 5 sensing data provided by LEGOS. The point where model dots are closest to the dotted line
 6 was taken as the precipitation-scaling factor for each basin.

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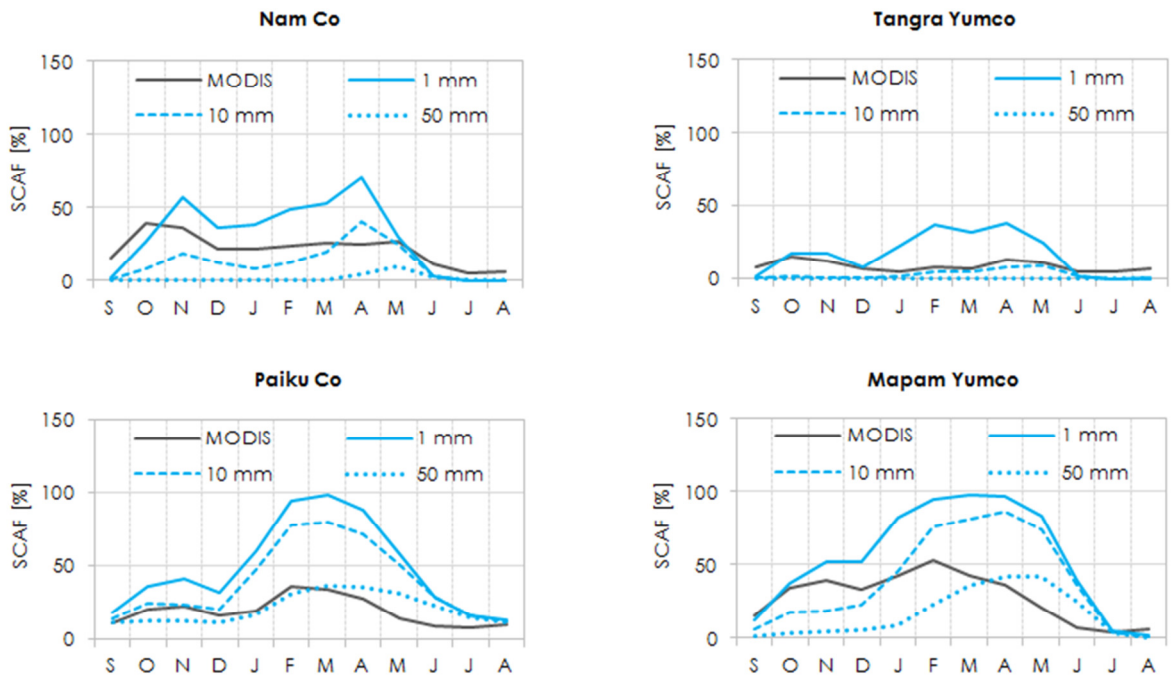
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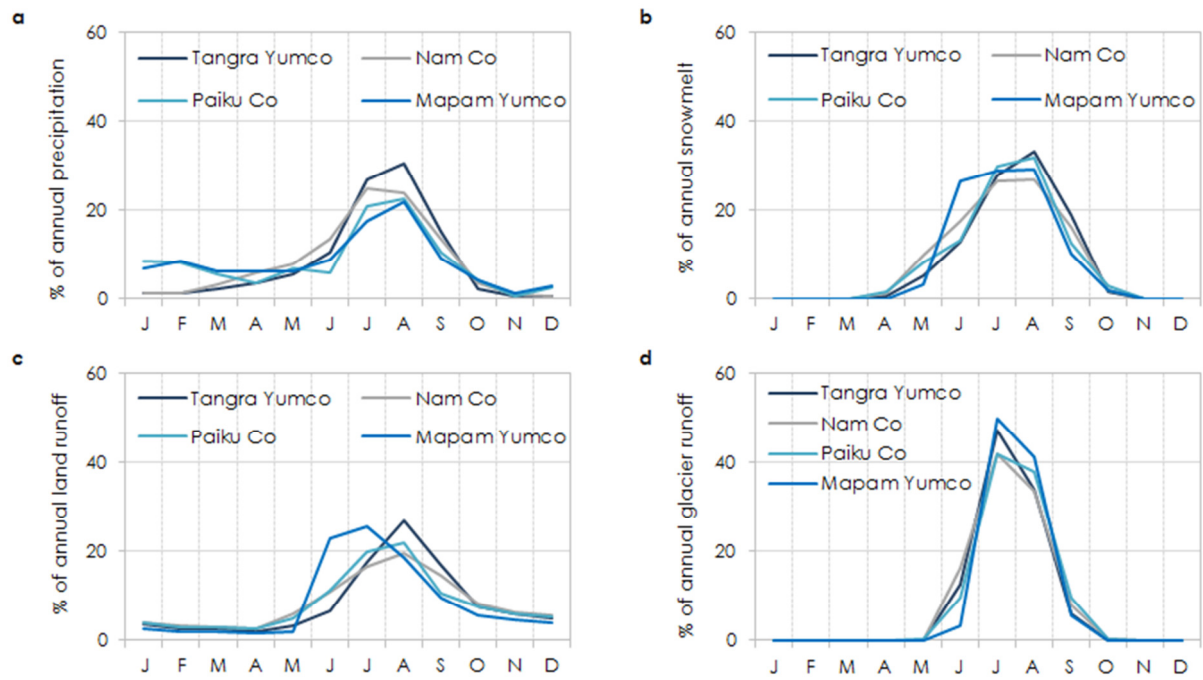
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2 Figure 4. Mean monthly modeled-derived SCAF (blue) using SWE > 1 mm (solid line), > 10
 3 mm (dashed line), and > 50 mm (dotted line) versus SCAF derived from MODIS (black) for
 4 the four study basins.



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2 Figure 5. (a) Monthly percentage of annual precipitation, (b) snowmelt from non-glacierized
 3 land areas, (c) runoff from non-glacierized land areas, and (d) glacier runoff for the four
 4 studied basins.

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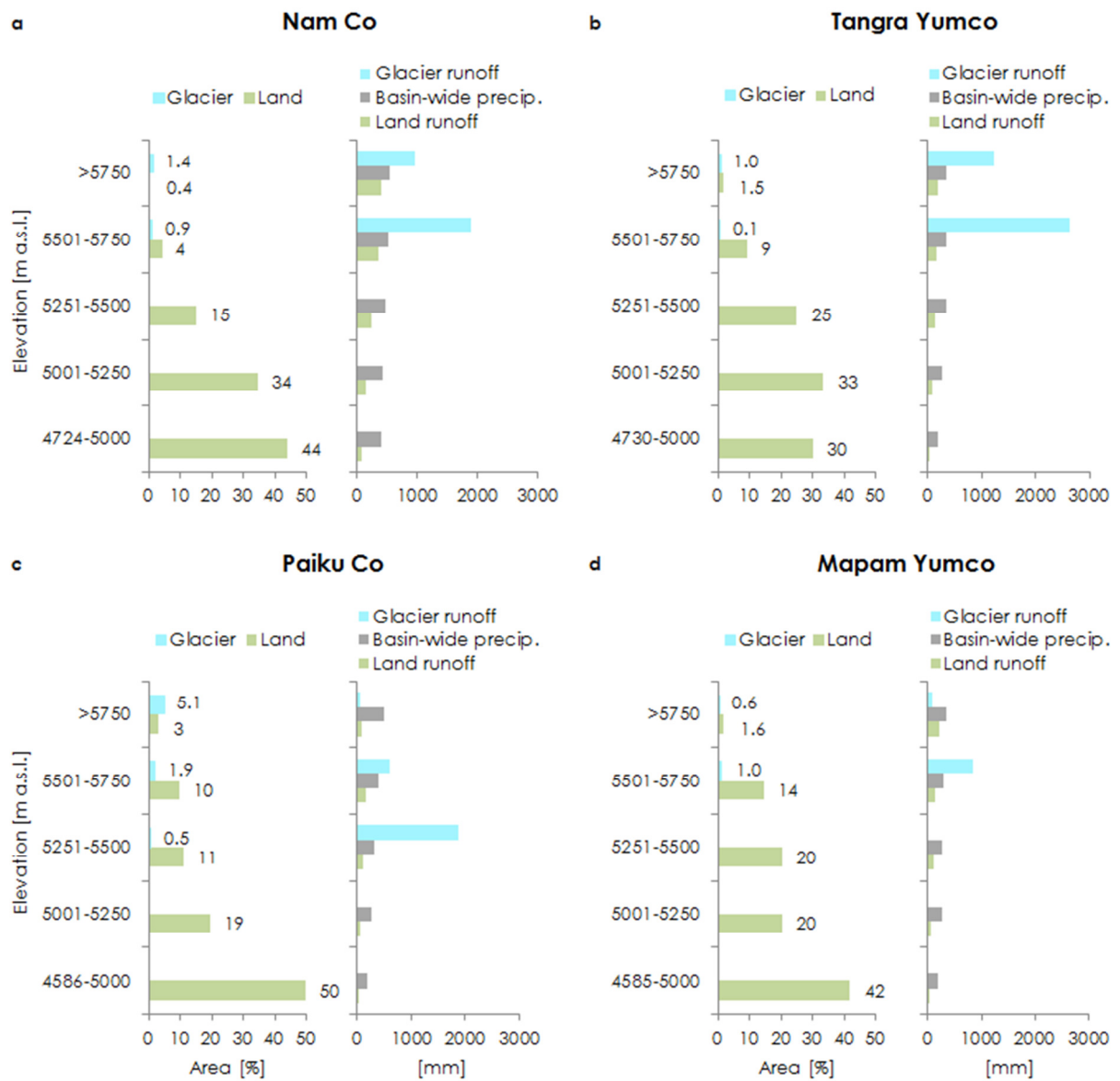
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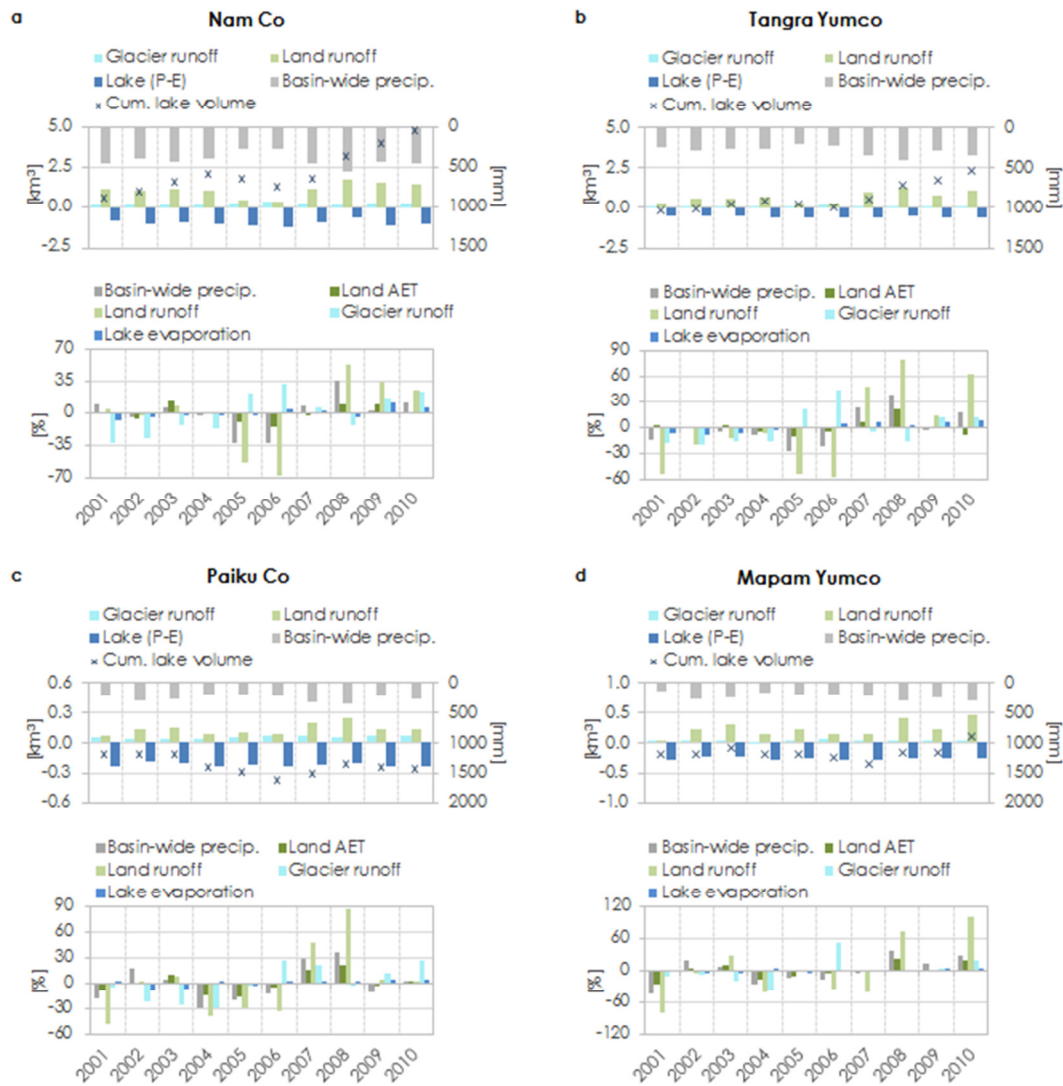
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Figure 6. (a-d, left panels) Hypsometry of glacier and non-glacierized areas based on mean elevations of respective model entities for the four studied basin. (a-d, right panels) Variability of precipitation and runoff from glacier and non-glacierized areas related to altitude for the four studied basins.



1
 2 Figure 7. (a-d, upper panels) Cumulative lake-volume change (km^3), contribution of several
 3 water-balance components (km^3) to lake-volume change and annual basin-wide precipitation
 4 amounts (mm yr^{-1}) for the four studied basins. (a-d, lower panels) Annual percentage
 5 deviations from the 10-year average of several water-balance components for the four studied
 6 basins.