A reflection on the long-term water balance of the Upper Indus Basin

P. Reggiani and T. H. M. Rientjes

ABSTRACT

Rapid glacier retreats due to rising temperatures have been predicted in the Hindukush–Karakoram–Himalaya (HKKH). Recent findings indicate shrinking glaciers in parts of the Himalayas, affecting ice storage and ultimately water availability. Insights on ice storage of the HKKH remain controversial, where glaciers retreat in some parts, while surging in others. In high-altitude areas only few *in-situ* observations are available, leading to ambiguous closure of the hydrological balance. Objective of this paper is to analyze the closure for the Upper Indus Basin (UIB). A first-order analysis using long-term flow and precipitation records, estimates of evaporation and ice storage is performed. Satellite information, atmospheric reanalyses, *in-situ* observations and related uncertainty are independently investigated. Trend analysis of 50-year stream flow indicates a statistically insignificant decrease of basin outflow. Analysis of 100-year precipitation data at valley stations shows no significant long-term trend, whereas temperature has increased moderately. Estimates of evaporation and sublimation in the HKKH system are notably few. Findings suggest that a substantial loss of ice in the UIB during the 1999–2009 decade is unlikely. Ice storage is probably at equilibrium or under slight accumulation, as indicated by recent altimetry studies in the Karakoram. In the UIB there is no evidence for intermediate-term risk to water supply as suggested in recent literature.

Key words | GCM, hydrological modeling, *in-situ* data, remote sensing, Upper Indus Basin, water balance closure

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INTRODUCTION

The Himalayas and the Tibetan Plateau host the origins of Asia's most important rivers that constitute essential life support streams for more than a billion people inhabiting a large part of the continent. Their flows reach low-lying downstream regions, where water is used for irrigation and human consumption. By projections on climate change, rapid glacier retreats have been predicted in the Himalayas at large and have triggered research on ice storage dynamics in the glaciated mountain ranges. Research aimed at assessing possible imbalances for future periods has led to concerns about looming water supply constraints for large populations. Sound water resources assessments require closure of the water balance as well as an indication on possible uncertainty affecting individual closure terms. In the Upper Indus Basin (UIB) and nearby mountain ranges both of these aspects require further investigations.

In this study we aim to contribute towards discussing the closure of the hydrological water balance for the portion of the Hindukush–Karakoram–Himalaya (HKKH) system, which lies within the Indus Basin boundaries, is shared by Pakistan, India and China and is referred to as the UIB. We propose to close the water balance by quantifying the main balance terms at the first order due to severe lack of data for certain balance terms at the sub-annual time scale. In our approach all balance terms are associated with meaningful uncertainty to indicate closure error ranges.

In this paper recent research findings on ice storage dynamics and glacier melt are evaluated and combined

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with trend analysis of 100-year precipitation and 50-year stream flow data on a daily basis. We estimate atmospheric water demand by evaporation and sublimation, which has been addressed weakly or simply ignored in a number of recent studies. Results of various satellite applications and global circulation models (GCMs) in the HKKH system are also evaluated. These observations serve as alternative sources of information on this remote and inaccessible region due to lack of *in-situ* data. For the same reason, satellite observations lack rigorous validation or correction.

Winiger *et al.* (2005) indicate that for the Indus basin about 50% of flow originates from snow and glacial melt in the HKKH. Savoskul & Smakhtin (2013) in a more recent report show 35–40% of melt contribution. Immerzeel & Bierkens (2012) identified the Indus basin as a 'hot-spot' system on the basis of risk of future water deficits by climate change. Moreover, the UIB has a relatively high contribution of snow and glacial melt to Indus flows compared to the Ganges and Brahmaputra. The dry and densely populated lower Indus Basin contributes little to the regional water budget relative to its size.

Studies by Hewitt (2005) & Cogley (2012) indicate that the Indus Basin is particular in terms of ice storage and glacier dynamics, as some glaciers in the central Karakoram are either in equilibrium or surging since the 1980s, a phenomenon referred to as 'Karakoram anomaly' due to the locally anomalous glacier dynamics trend against the remaining part of the HKKH. One possible explanation is warming and greater transport of moisture to higher altitudes, leading to sudden and sproradic glacier expansions (Hewitt 2005). Findings on the 'Karakoram anomaly' have been corroborated by field surveys in the wider region (Raina 2009; Schmidt & Nüsser 2009; Vincent *et al.* 2013) and contemporary satellite-based altimetry studies, in which glacier ice storage has been analysed during the last decade. Gardelle *et al.* (2012a) compared surface elevation data from the February 2000 Shuttle Radar Topographic Mission (SRTM) with SPOT5 optical stereo imagery acquired in 2008 and indicated increased glacier ice storage in the central Karakoram range. Earlier assumptions on the contribution of the Karakoram glacial melt water to sea level rise during the first decade of the 21st century need therefore to be revised from earlier positive (Church *et al.* 2011) (+0.04 mm/yr) to negative (−0.01 mm/yr) estimates (Gardner *et al.* 2013). This positive trend in glacier ice storage has been confirmed for the 1999–2011 period (Gardelle *et al.* 2013), and also observed for glaciers in the Pamir region. Kääb *et al.* (2012) performed satellite-based ice storage investigations using ICESat, SRTM and ASTER elevation data over the 2003–2008 period, and came to the conclusion that glacier ice storage has decreased in the HKKH as a whole, but storage has locally increased in the Karakoram or has remained neutral in the northern part of the Hindukush range. These findings are also shown to exhibit the same declining ice storage trend in the HKKH, but stronger than detected by space-borne gravimetric measurements (Jacob *et al.* 2012). Scherler *et al.* (2011) and Gardelle *et al.* (2012b), in more detail, suggest that the degree of glacier thinning in the Karakoram depends on spatial gradients of debris cover. Most of these studies do not include a comprehensive hydrologic water balance analysis to conclude on possible water supply impacts for future periods. Also, water balance closure is not shown and not placed in an uncertainty framework.

The loss (or gain) of glacier ice, which has been analysed in a spatially distributed way in the above investigations should, in principle, be reflected in the observed basin outflow signal when climatic forcing has not notably changed. The link between changes in glacier ice storage, outflow and climate is provided by the basin water balance equation. A major stumbling block for assessments is the scarcity of *in-situ* data in the large and inaccessible region. For instance, from the existing precipitation monitoring network in the UIB, only nine stations can be considered representative for the area under study and need to be separated from less representative ones located at lower altitudes on the Himalayan foothills facing the Lower Indus Basin. Stations, however, are unevenly distributed and historically located in the valleys because of site accessibility. As far as evaporation and sublimation is concerned, very little data have been collected thus far in nival and glaciated regions in the UIB, the HKKH, and Himalayas at large. As such any estimate for the UIB must be associated with considerable uncertainty. As an alternative to *in-situ* observations, we examined the suitability of satellite data and results from GCMs to evaluate the water balance and its closure, as these are used in various

hydrological studies for the HKKH. In light of the above, three inconsistencies emerge on the UIB water balance against the background of endemic data scarcity and recently published research:

- First, we note that the outflow from the UIB, which is observed at Besham Qila, just upstream of Tarbela reservoir (164,475 km^2 of drainage area), exhibits a slight decreasing trend since earliest measurements in 1961. However, a decreasing outflow is in contrast with the hypothesis of retreating glaciers and increased ice melt in the UIB, as suggested by satellite altimetry and gravimetric data.
- Second, flow observations at the level of sub-basins show that annual outflows from strongly glaciated high-altitude subsystems in the UIB, such as the Hunza, Shyok and Shigar, are decreasing (Hunza) or stable (Shyok, Shigar) over the last decades, indicating that precipitation is either decreasing, or unchanged and stored as ice. On the other hand, outflows from the lower-altitude sub-basins, such as the Gilgit, the Astore or the eastern Indus on the Tibetan Plateau, with a predominantly nival runoff regime, have been increasing (Archer 2003; Sharif *et al.* 2013). If the increased outflow from the nival sub-basins of the UIB is added to the effect of glacier melt, as suggested by gravimetric and/or altimetry studies, the overall basin outflow at Besham should increase instead of decreasing as observed.
- Third, modelling studies (Immerzeel *et al.* 2009; Bookhagen & Burbank 2010), which are driven by satellite-based precipitation estimates, indicate an outflow at Besham Qila, which is larger than the precipitation used to drive the models. In the first study it is reasoned that excess discharge must be attributable to ongoing glacier wastage. In both studies evapotranspiration is not extensively assessed and precipitation estimates require further validation. Both aspects constrain water balance assessment and make closure doubtful.

In this paper we address the above inconsistencies in detail and aim to close the UIB water balance by also considering uncertainty. We cover five topics: (1) the basin water balance, (2) basin outflow, (3) precipitation, (4) evaporation and (5) the implications on glacier mass storage.

BASIN MASS BALANCE

Starting from first principles in water balance assessments, the time-average water balance equation (Reggiani *et al.* 1998) for the UIB upstream of Besham Qila station can be stated as follows:

$$E\left[\frac{\mathrm{d}V}{\mathrm{d}t}\right] = E[P - ET - Q - G] \tag{1}$$

where $E[\ \ ]$ is the expected value operator, Q is the stream outflow at a control section, P is the precipitation and ET is actual evaporation and sublimation. The net input for the system is given by $P - ET$, while G represents losses (i.e., recharge) to deeper groundwater. It is reasonable to assume that the mean annual groundwater recharge flux $E[G] \approx 0$, as part of the snow and glacial melt water finds its way towards the outlet through fast surface runoff or return flows from the shallow groundwater systems in alluvial formations, which operate as transient flow buffers (Kemmerikh 1972; Andermann *et al.* 2012; Savoskul & Smakhtin 2013). Extended groundwater storage dynamics commonly relate to deep, fluvial systems with long, multi-decadal time-scales of flow. The rate of change $\mathrm{d}V/\mathrm{d}t$ accounts for all water going into storage if the derivative is positive, or storage depletion, if the derivative is negative. In the UIB, the principal and most dynamic storage consists of snow pack and glacier ice. The water balance equation (Equation (1)) can therefore be applied to the entire UIB, with closing section at Besham Qila (Figure 1). Below we address and quantify each individual term.

Outflow

A first step to assess impacts of climate change on future surface water availability is to perform a Mann–Kendall (MK) trend analysis on long-term stream flow data. For the UIB, flow data is collected by the Pakistani Water and Power Development Authority (WAPDA), which maintains a series of stream flow gauging stations. In most UIB studies, Besham Qila is selected as the stream flow station for analysis. It is located roughly 60 km upstream from Tarbela reservoir. The reservoir was commissioned in 1976 and daily inflow measurements exist since 1961. For consistency

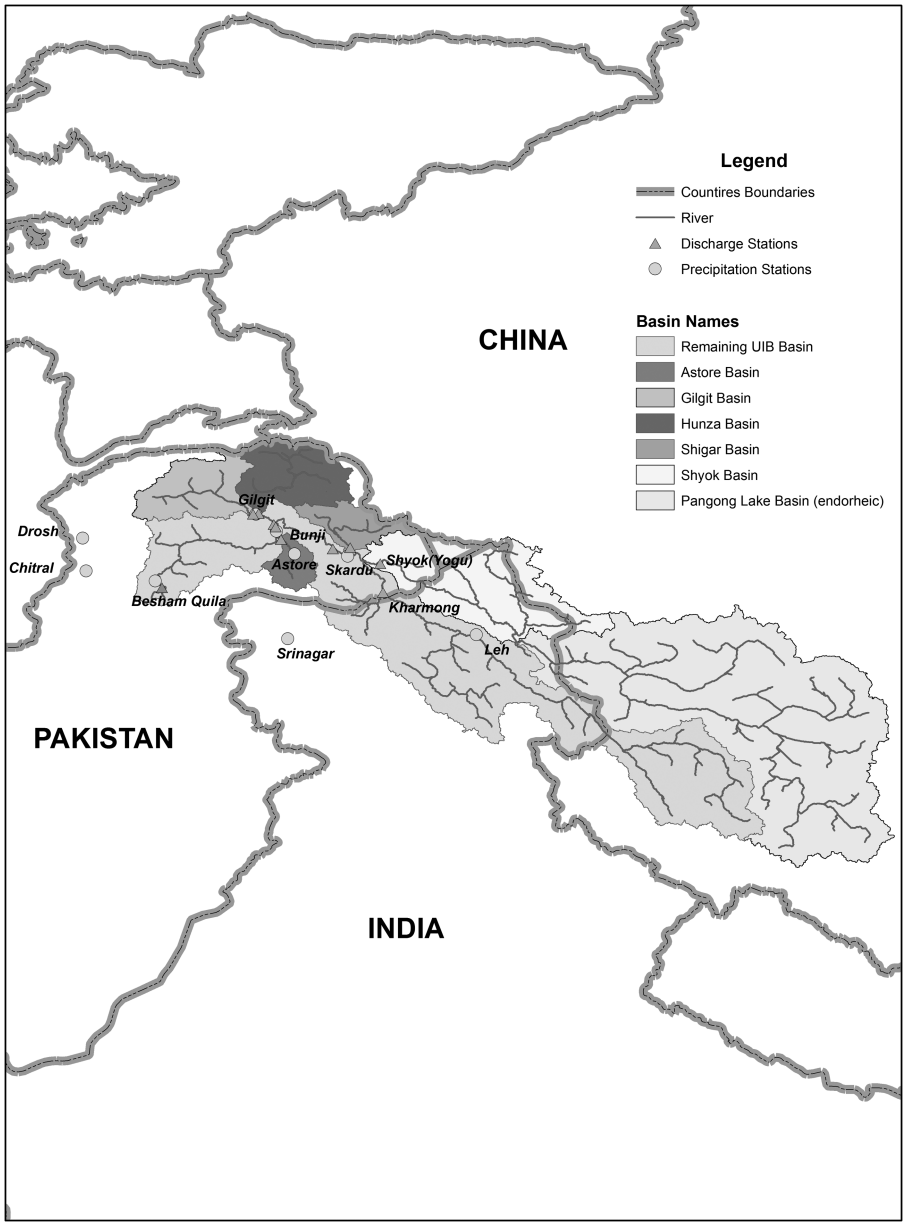

Figure 1 | Map showing the boundaries of the UIB and the principal hydro-meteorological observation stations.

of units in the water balance, we convert and average long-term, daily stream flow records expressed in [m^3/s] to annual basin yields expressed in [mm], which requires knowledge of the upstream basin surface area. At Besham Qila, Bookhagen & Burbank (2010) estimated an upstream area of 205,536 km^2, Mukhopadhyay & Dutta (2010) an area of 265,598 km^2, whereas Young & Hewitt (1990) indicated 162,393 km^2 (Table 1), a number in line with WAPDA reservoir data. The difference in basin surface area is approximately 25 to 60%. The area differences are merely due to the accounting of peripheral areas, such as the Pangong Lake subcatchment, which are endorheic, and thus do not contribute towards the downstream basin (Alford 2011; Sharif *et al.* 2013; Khan *et al.* 2014). Obviously, a consistent surface area matters when comparing basin yields for water balance purposes by the various studies reported. In

Table 1 | UIB data upstream of Besham Qila as published in the literature

Author	Period	Q [mm/yr]*	P [mm]	ET [mm]	Area [km^2]
Observations (WAPDA)	1961–2009	462	n/a	n/a	162,393
Young & Hewitt (1990)	1969–1975	457	n/a	n/a	162,393
Immerzeel *et al.* (2009)	2001–2005	360	311	n/a	200,677
Immerzeel *et al.* (2010)	2001–2005	444	311	n/a	162,393
Bookhagen Burbank (2010)	1998–2007	644	300	15	205,536
Tahir *et al.* (2011)	1974–2008	376	n/a	n/a	201,388
Sharif *et al.* (2013)	1969–1997	458	n/a	n/a	166,069$^+$
Khan *et al.* (2014)	n/a	n/a	n/a	n/a	164,867
This study	1961–2009	456	675 ± 100	200 ± 100	164,475

*Flows are normalized using the basin surface areas reported in the last column.
$^+$Area reported by Alford (2011).

this work we estimated a surface area of 164,475 km^2 from the Shuttle Radar Topography Mission (SRTM) 90 m × 90 m DEM by use of the TARDEM digital terrain analysis package (Tarboton 1997). In the process of area computation we used the infinite flow direction option (d∞), and eliminated endorheic areas of the basin on the Tibetan Plateau. Our area estimate is within 1% of the figure indicated by Young & Hewitt (1990), WAPDA and Alford (2011) and practically coinciding with the very recent estimate by Khan *et al.* (2014) (Table 1).

Analysis of the stream flow time series at Besham Qila indicates that the flow has been relatively stable at around 2,380 m^3/s during the last 50 years, as shown by the decadal reservoir inflow volumes in Table 2 and Figure 2. This corresponds to an annual basin yield of 456 mm using a surface area of 164,475 km^2. The annual yield for the 1999–2009 decade is slightly below the long-term mean with a value of 436 mm, equivalent to a flow of 2,273 m^3/s. Young & Hewitt (1990) report an average flow of 2,352 m^3/s for 1969–1975, Tahir *et al.* (2011) 2,410 m^3/s for 1969–2008 and Immerzeel *et al.* (2009) 2,289 m^3/s for 2001–2005. Reported average flow rates are affected by the different observation periods, but deviations are only small, indicating an overall stable long-term annual outflow with no significant trend (Khan 2001; Khattak *et al.* 2011; Sharif *et al.* 2013). We note that during the 1999–2009 decade, a moderate flow decrease with respect to the long-term mean is recognizable (Table 2). Trend analysis in this study using the MK, Pearson and Spearman tests on the Besham Qila time series (1961–2009) indicates a weak, statistically insignificant ($p > 0.1$) decreasing trend, whereas Sharif *et al.* (2013) indicate a weak, statistically insignificant increasing trend for the period 1969–1997. The analysis in this study indicates that the difference in the weak trend is due to their 20 years shorter stream flow record.

Table 2 | Tarbela reservoir decadal inflow 1961–2009

Decade	Inflow [mm/yr] $^+$	Deviation [mm/yr]	(%)
1961–1969	472	+ 16.0	+ 3.46
1969–-1979	458	+ 1.2	+ 0.26
1979–1989	438	− 19.0	− 4.11
1989–1999	479	+ 22.0	+ 4.89
1999–2009	436	− 21.0	− 4.50
Mean	456 (2,380 m^3/s)		

Source: WAPDA, Pakistan.
$^+$All flows are normalized using a basin surface area of 164,475 km^2.

A closer look at the sub-basins of the Upper Indus reveals contrasting trends of long-term average flow rates. This applies to the strongly glaciated Hunza (13,925 km^2 at Dainyore), Shigar (7,382 km^2 at Shigar bridge) and Shyok River (33,350 km^2 at Yogu) basins to the north and the less glaciated more nival (Archer 2003) dominated Astore (3,750 km^2 at Doyian), Gilgit (12,800 km^2 at Gilgit) and the Indus at Katchura (115,289 km^2) and Kharmong (72,500 km^2) located to the south, west and east, respectively. Stream flow data analyses for these sub-basins (Fowler & Archer 2006; Bocchiola *et al.* 2011; Naz 2011;

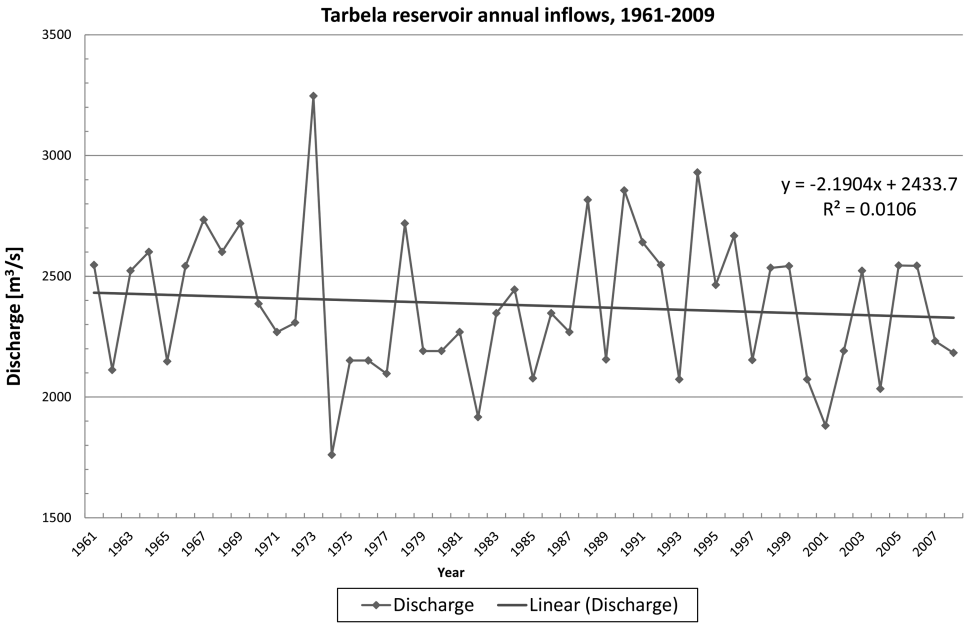

Figure 2 | Tarbela reservoir inflows observed at Besham Qila over 1961–2009. The thick solid line indicates a statistically insignificant declining trend over the observation period. Source: Water and Power Development Authority, Pakistan.

Khattak *et al.* 2011; Mukhopadhyay 2012; Sharif *et al.* 2013) have been performed over the period 1970–2005 using series of different length according to data availability.

Findings on statistically significant trends show consistency between studies and can be recapitulated as follows: significant increasing flow trends during the spring and summer snow melt season were found in all studies for the nival Astore and Gilgit Basins and the Indus at Kachura, whereas a significant decreasing spring and summer trend was assessed for the Hunza River. No statistically significant spring or summer trend is observed for the Shyok. Fowler & Archer (2006) provide an indication on the extent of decrease of flow in the Hunza over 1961–2000 with flow rates decreasing by 46 and 35% during the spring and summer season, respectively, over the record period, which is a very substantial amount. Flow records (1970–2004) for the Gilgit River at Alam Bridge (just downstream of the confluence with the Hunza, 27,525 km^2 of combined upstream basin area) indicate also a significant downward trend during summer for the merged flows of the two rivers (Sharif *et al.* 2013).

On an annual basis the following is common to all trend studies: the Hunza and Indus at Kharmong (15 years of data only) show a statistically significant declining annual trend, whereas the Astore and the Gilgit show a significantly increasing trend. No significant annual trend is indicated for the heavily glaciated Shyok and Shigar. The Indus at Katchura (including the Shyok and Shigar Basins) shows a significant increasing annual trend over the 1979–1997 period. We note that increases at Katchura are unlikely to be caused by the Shrigar and the much larger Shyok basins, which both show stable records over the same period. Assuming that the flow data is not subject to measurement errors (i.e., outdated or unreliable stage-discharge rating curves due to changing river bed geometry), this increase is likely caused by growing seasonal snowmelt contribution from the Tibetan Plateau upstream of Katchura and Kharmong.

These opposing flow trends in the sub-basins of the Upper Indus are not in contradiction with the overall behaviour observed at Besham Qila and indicate that precipitation (i.e., snow) may be going into storage in one part of the basin, while in other parts glacier ice storage may be reduced. In sub-basins with a more nival regime like the Gilgit and Astore, changes in outflow may be more likely a result of precipitation by rainfall, which directly causes stream flow to increase. An investigation of basin-internal spatial pattern of (cryospheric) glacier ice storage changes

is not pursued here, since it is beyond the scope of this study. Also, collecting *in-situ* assessments is very resource intensive (Cogley 2012), and measurements should be performed over extended periods of time. We recommend extending glacier investigations and field surveys using the methods listed in Gardelle *et al.* (2013).

Precipitation

The estimation of precipitation across the entire UIB is difficult due to the extreme topography and the low number of gauging stations, which are situated mainly in the valleys at relatively low altitude in the high mountain ranges. Archer & Fowler (2004) studied long-term precipitation and temperature series from 17 stations which were partly installed in the late 19th century with some recording gap during the transition from British to Pakistani independent administration. The longest data series analysed cover the period 1895–1999. In the same work, it is described that the records exhibit a complex season-dependent spatial correlation structure. Over the last century, no statistically significant long-term trends could be detected for annual and seasonal precipitation although for the 1961–1999 period increases in winter and summer precipitation are reported at some stations. A closer look at the network of 17 stations shows that not all stations should be considered. To obtain a representative basin-average precipitation estimate, we selected an ensemble of nine stations (Figure 1, Table 3). The rationale behind the selection is that Upper Indus valleys are characterized by arid climate, whereas the southern part of the basin at lower elevation is affected by the much wetter monsoon climate. The chosen stations represent an as good as possible ensemble, covering precipitation-elevation zones between 480 and 3,506 m above sea level. For the very high altitudes (>3,500 m), which constitute a substantial portion of the basin, stations are not available, constraining accurate basin-wide precipitation estimates and representation. For the ensemble of nine stations, an arithmetic average precipitation of 438 mm/yr is calculated. Since density of the unevenly distributed stations is low (approx. 1 gauge/20,000 km^2), time series cannot be used directly for basin-scale water balance assessments.

Table 3 | Annual precipitation in the UIB and arithmetic mean (Archer & Fowler (2004))

Station	Period	P [mm/yr]	Altitude [m]
Chitral	1965–1991	441.7	1,499
Drosh	1931–1997	636.8	1,465
Gilgit	1884–1999	131.2	1,460
Bunji	1952–1970	126.3	1,372
Astore	1954–1997	516.7	2,394
Skardu	1894–1999	222.3	2,210
Srinagar	1893–1999	683.0	1,584
Leh (Kashmir)	1882–1968	92.7	3,506
Besham	1970–1997	1098.8	480
Mean		438.8	1,774

In the face of considerable difficulties of sampling precipitation in this region, Miehe *et al.* (2001) report cumulative annual precipitation values of 600 mm/yr and higher at altitudes of 4,000 m in the central-north western Karakoram, whereas Kuhle (2005) suggests accumulation rates up to 2,000 mm/yr for very high altitudes up to 7,000 m in the Karakoram. For the same area, Winiger *et al.* (2005) measures 1,700 mm/yr water equivalent (w.e.) above 5,500 m. Glacio-chemical field studies (Hewitt *et al.* 1989; Wake 1989) at the Biafo and Khurdopin glaciers, central Karakoram, suggest annual accumulation rates from 0.9 to 1.9 m of w.e. between 4,650 and 5,500 m. Young & Hewitt (1990) and Cramer (2000) state that cumulative precipitation in the HKKH is much larger at high elevation zones than in the valleys, although above 6,000 m of altitude precipitation is known to decrease again. Hewitt (2011) describes that vertical air humidity correlates with altitude, thus observations at lower altitudes must be revised upwards to account for orographic and horizontal wind redistribution effects. Medina *et al.* (2010) show for the Himalayas that large scale air flow and specific mountain geometry may interact, resulting in significant precipitation. Findings from the above studies at very high altitude suggest that average precipitation in the UIB is significantly higher than the 438 mm/yr average precipitation for the network of valley stations. Altitude corrections commonly are applied based on a defined elevation-precipitation lapse rate. However, as pointed out by Yatagai & Kawamoto (2009), for the UIB *in-situ* stations are only few and their wide spread does not allow to quantify a reliable lapse rate for a systematic correction of *in-situ* precipitation observations. When

combining the average precipitation of 438 mm/yr for the nine valley stations with findings from the very high altitude studies, this suggests that average precipitation for the UIB requires upward correction. Walter & Lieth (1967) and Young & Hewitt (1990) show that the eastern part of the UIB is significantly dryer (e.g., Table 3, station Leh, 3,506 m, with $P < 100$ mm/yr) than the western part, which covers most of the 60% of the UIB area above 4,500 m. Also in the western part, snowfall occurs during the entire year by summer monsoon and by mid-latitude pressure systems that bring moisture to the region (Ménégoz *et al.* 2013). As such, it is not plausible to assume that the average annual precipitation in the UIB is much lower than 600 mm/yr. We will substantiate the estimate further below.

For estimation of basin-wide precipitation, satellite imagery provides an alternative to the use of *in-situ* data. The premise and main advantage of satellite approaches are that the gridded satellite-based precipitation products cover large areas and that observations can be repeated over time. Principle to satellite applications is that observations require validation by comparison to ground truth. First examples of satellite precipitation estimation in the UIB are provided by Immerzeel *et al.* (2009) and Bookhagen & Burbank (2010), who selected the Tropical Rainfall Measuring Mission (TRMM) satellite-based precipitation product TRMM 2B31 (monthly data, $0.5^\circ \times 0.5^\circ$ resolution). Results after spatial averaging across the UIB showed average annual precipitation of respectively 311 and 300 mm/yr. In neither study the satellite products were bias corrected, presumably due to lack of representative ground truth data. As such estimates are highly uncertain and thus doubtful for use in water balance assessments. Forsythe *et al.* (2011) compared TRMM 3B43 (monthly data, $0.25^\circ \times 0.25^\circ$ resolution) derived precipitation in the UIB to the sparsely available *in-situ* observations and concluded that the TRMM product is a quantitative indicator of monthly rainfall abundance rather than a measure of absolute magnitude. Their comparisons with *in-situ* weather stations demonstrate that the product does not capture the orographically driven gradients and stratification of precipitation well, leading to underestimations of cumulative precipitation by 40 to 60%. Similar conclusions for high-altitude applications of the TRMM 3B43 product were drawn by Condom *et al.* (2011) and Ward *et al.* (2011) for the wet season in the Peruvian and Ecuadorian Andes, respectively. This suggests that the actual UIB annual precipitation would be more than double the TRMM estimate or considerably above 600 mm/yr, whereby the actual precipitation deviates locally from this average in response to the extreme topographic relief.

A second alternative to the use of *in-situ* data for estimation of spatially averaged basin-wide precipitation in the UIB is shown by snowmelt runoff modelling where precipitation amount is inversely estimated to match observed stream flow by snow melt and direct runoff (Immerzeel *et al.* 2012). Findings indicate that the annual average precipitation in the Hunza sub-basin is severely underestimated by valley stations and it is suggested that basin-wide precipitation should be above 800 mm/yr. However, we note that evaporation and sublimation from the UIB were basically ignored in this study and thus reliability of the precipitation estimate by closure of the water balance is unclear. The net system input $P - ET$ requires downward correction to account for losses by evaporation and sublimation.

Recent studies by Ménégoz *et al.* (2013) and Palazzi *et al.* (2013) report on a number of precipitation estimation products in the HKKH region and Himalayas. In Ménégoz *et al.* (2013), estimates by the Modèle Atmosphérique Régional (MAR) Regional Climate Model (RCM) are compared against a number of advanced satellite-based and network-based gridded products for the more eastern part of Himalayas, excluding the UIB. Although specific results for the UIB are not reported, it is indicated that snow depth is often underestimated by rain gauges, but also that across the Himalayas precipitation estimates differ widely according to the different data sources, with a very large uncertainty range between 100 and 500 mm per month. With reference to studies by Dimri & Niyogi (2013) and Dimri *et al.* (2013), Ménégoz *et al.* (2013) describe that RCMs lack the capacity to separate correctly between liquid and solid phase precipitation, constraining direct applicability in hydrology and glaciology.

In Palazzi *et al.* (2013), a number of coarse-scale ($\geq 0.25^\circ \times 0.25^\circ$ resolution) precipitation products are evaluated and mutually inter-compared for the HKKH region and eastern Himalayas. Gridded, network-based products are Climate Research Unit (CRU) TS3.1 (Harris *et al.*

2013), Global Precipitation Climatology Centre (GPCC) gridded observation reanalysis (Schneider *et al.* 2011) and the APHRODITE dataset (Yatagai *et al.* 2012, 2009). The Global Precipitation Climatology Project is a merged precipitation-observation product, ERA-Interim (Dee *et al.* 2011) an atmospheric reanalysis (1979–2013) product and EC-Earth a GCM (re)forecast from 1950 to the present (Hazeleger *et al.* 2012). It is described that the study did not aim to define ground 'truth' or a reference data set, but to highlight the biases between the products, their similarities and discrepancies. Overall it was shown that all products reproduced seasonal variability, but also that precipitation estimates by the products differ widely. This is partly because network-based estimates as well as TRMM 3B42 primarily observe liquid precipitation, whereas ERA-Interim and EC-Earth also estimate solid precipitation (Palazzi *et al.* 2013). For their 71°–78°E/32°–37°N HKK (Hindukush–Karakoram) analysis window, including only part of the western and central UIB, a low estimate by GPCC is approximately 480 mm of annual precipitation, whereas the highest estimate by ERA-Interim is approximately 950 mm.

To estimate annual precipitation for our water balance assessment, we computed average total precipitation (liquid and snow) over 1998–2009, using the UIB boundary mask indicated in Figure 1 under exclusion of the endorheic Pangong Lake catchment area, with the (1) uncorrected, (2) the network-corrected ERA-Interim reanalysis and (3) the uncorrected NCEP/NCAR reanalysis product (Kalnay *et al.* 1996). The corrected ERA-Interim reanalysis, known as WATCH Forcing Data ERA-Interim (WFDEI) (Weedon *et al.* 2011), is based on CRU TS3.1 and GPCC precipitation data for model output correction, whereby we note that the support stations for this operation are the same few that we have selected. Characteristics for all products compared are summarized in Table 4. Own estimates resulted in basin averages between 705 mm (NCEP/NCAR reanalysis), 681 mm (uncorrected ERA-Interim reanalysis) and 291 mm (network-corrected ERA-Interim WFDEI data), respectively. The climatology of all precipitation products is reported in Figure 3, the resulting UIB mean annual precipitation in Table 4.

The correction of the ERA-Interim product caused a down-weighting of the areal precipitation due to use of stations which are situated in the dryer valleys. For this reason, we assume the higher estimate derived from the uncorrected ERA-Interim and NCEP/NCAR reanalysis to be more reliable. This suggests that annual precipitation is approximately in the value range of 675 mm ± 100 mm, whereby we decided to rely on the ERA-Interim precipitation estimate because of the considerably higher spatial resolution ($0.5^\circ \times 0.5^\circ$ vs. $1.875^\circ \times 1.875^\circ$, Table 4) of the product that allows a more accurate averaging along the basin boundaries. The large uncertainty, which we associate with the estimate, accounts for possible bias of the estimate that cannot be quantified or removed due to absence of ground stations at high altitudes. In the reported studies, it was indicated that products are very uncertain over mountainous areas and that the lack of *in-situ* stations was considered a major constraint to validation. Uncorrected results may also require a downward correction to account for valley areas that make up a small part of the basin area.

Table 4 | Main characteristics of the observational and reanalysis products analysed for the UIB for 1998–2009. ERA-Interim provides actual evaporation estimates and is therefore not included

Data set	Product	Data range	Spatial res. original product	Temporal resolution	Mean precipitation [mm/yr]	Mean pot. evaporation [mm/yr]
TRMM	3B42	1989–2010	$0.25^\circ \times 0.25^\circ$	3-hourly	310	n/a
GPCC	Version 2011 reanalysis	1901–2010	$0.5^\circ \times 0.5^\circ$	monthly	279	n/a
ERA-Interim	Reanalysis	1979–2012	$0.75^\circ \times 0.75^\circ$+	daily	681	n/a
WFDEI	2013 release	1979–2012	$0.5^\circ \times 0.5^\circ$	daily	291	734
CRU 3.21	Version 3.21	1901–2012	$0.5^\circ \times 0.5^\circ$	monthly	341	833
NCEP/NCAR	Reanalysis monthly averages	1948–2012	$1.875^\circ \times 1.875^\circ$	monthly	705	807

+For this study the original ERA-Interim product has been regridded to $0.5^\circ \times 0.5^\circ$.

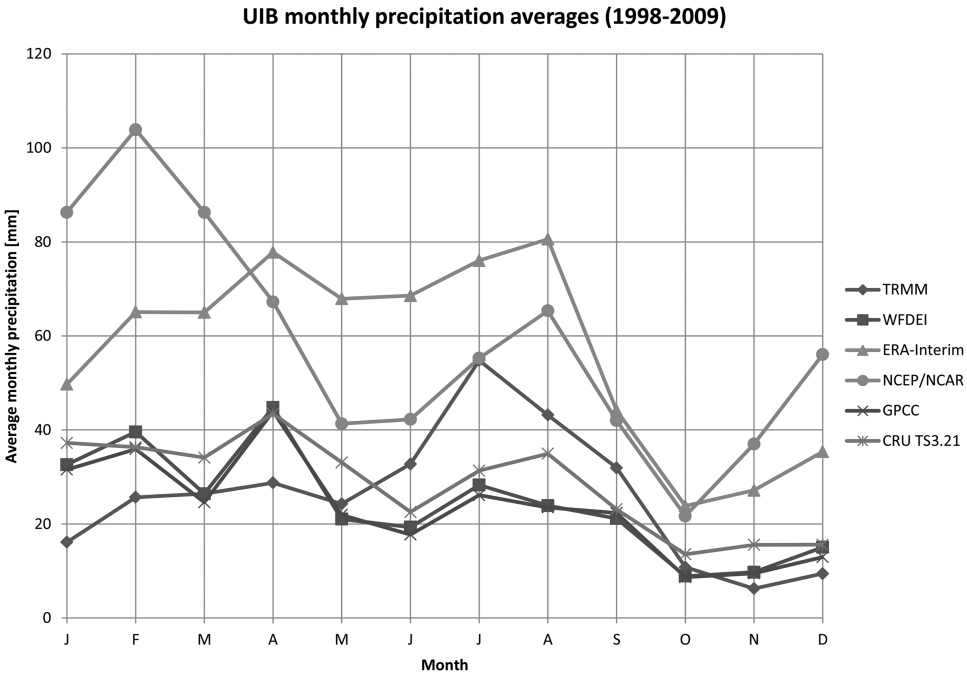

Figure 3 | Inter-comparison of the climatology of the precipitation products listed in Table 4 over 1998–2009.

In Palazzi *et al.* (2013), it was shown that atmospheric reanalysis by ERA-Interim (1979–2010) and the EC-Earth climate model simulations (1950–2010) did not have a clear trend of total precipitation in the UIB and HKK at large. We performed a MK test on the NCEP/NCAR reanalysis for the UIB (1979–2010) and found no significant trend of precipitation. Moreover, climate simulations with EC-Earth to 2100 indicate that stable precipitation in the HKK may persist for multiple decades into the future. Further analysis of climate change projections remains, however, beyond the scope of this paper.

To summarize on all the above findings, it is plausible to assume that there is no significant long-term trend in precipitation. For estimation of area-average precipitation, *in-situ* observations at the valley stations require upward correction. Also, studies on satellite-based precipitation products indicate that estimates require (substantial) upward correction. As shown before, findings consider doubling the satellite estimate to be realistic and suggest that precipitation could thus well be above 600 mm. Results from the atmospheric reanalyses suggest that precipitation in the UIB is in the range of 700 mm ± 100 mm. Findings from all three approaches indicate that precipitation is substantially higher than indicated by the arithmetic station average of 438 mm/yr in Table 3. Also, measurements at very high altitudes, although limited, indicate that the arithmetic average of 438 mm/yr for the valley stations must be revised upward. Combining all the above considerations leads to basin-average precipitation in the order of 675 mm ± 100 mm.

Evaporation and sublimation

Actual evaporation across the UIB varies in response to atmospheric forcing and moisture availability on snow and ice surfaces and on earth surfaces in the arid climatological conditions, which are covered by sand, gravel and sparse vegetation. The estimation of potential and actual evaporation in the UIB is intricate, given the almost total absence of ground stations at high altitudes and the high topographic heterogeneity. A classical indirect method of estimation, which has also been applied to alpine high-altitude areas, is to obtain actual evaporation from the water balance Equation (1), if $E[Q]$ and $E[P]$ are known (Swiss Academy of Sciences 1978). However, because of the few precipitation stations in the basin, this approach is impracticable. We assume that absence of ground stations is also the

main reason why estimates on evaporation and sublimation are ignored in many UIB water balance studies (Immerzeel *et al*. 2009; Tahir *et al*. 2011). An exception is in Bookhagen & Burbank (2010), who estimated actual evaporation at ca. 15 mm/yr. This suggests that actual evapotranspiration only is 2.2% of mean annual stream flow, which probably is very low.

A literature search on actual evaporation estimates at very high altitudes in the region leads to Bhutiyani (1999), who estimated evaporation rates for the period 1986 to 1991 to be used in a water balance study of Siachen glacier (Nubra valley, eastern Karakoram). Estimates at 4,800 m for the summer period on a yearly basis varied between 173 and 255 mm (average of 222 mm) with indicated observation uncertainty of 15–20%. The yearly average for the summer period is thus in the range 177 to 266 mm. Li & Ye (1998) give actual evaporation estimates for Tianshan Glaciological Station which serves China's glacier research. The station is located in the headwater area of the Urumqi River (43° 6′ 50″ N, 86° 50′ 33″ E, 3,545 m) in the Xinjiang Uygur Autonomous Region. Annual evaporation is measured at about 270 mm at the headwaters and the alpine meadow regions, but about 127 mm at the surface of Glacier No. 1 (4,000 m).

Alternatives to the use of *in-situ* data are estimates from Global Circulation Models (GCMs) and satellites. Potential evaporation from the NCEP/NCAR reanalysis and the ERA-Interim-derived WFDEI product give annual potential evaporation rates above 700 mm/yr for 1998–2009 (Table 4). Own MK testing of basin-average potential evaporation estimates since 1979 by the two products indicates that there is no trend over the last 30 years.

Satellite-based actual evaporation estimates are provided by MODIS-Terra spacecraft (MODerate resolution Imaging Spectroradiometer) as shown in Mu *et al*. (2007) and Cleugh *et al*. (2007) and used in Bookhagen & Burbank (2010). Estimates derived from the MOD16 evapotranspiration product for the UIB give an annual mean of less than 100 mm/yr. Since the product primarily serves estimation of transpiration by vegetation and evaporation from canopy and soil surfaces, accuracy for glaciated and snow covered areas in the UIB is uncertain. The product at a spatial resolution of 1 km × 1 km relies on MODIS land-cover, leaf area index and global surface meteorology from the Global Modelling and Assimilation Office of NASA.

In the view of this study, long-term changes in the UIB water balance by evaporation and sublimation could be directly affected by changes in radiation or air temperature. Kehrwald *et al*. (2008), examining ice cores, found no evidence for an increase of sublimation since 1950 at Naimona'nyi Glacier (30°27.06′ N, 81°91.94′ E, 6,050 m), Tibet, after being stable from 1880 to 1950. As such, there is little reason to assume that radiative forcing has changed in the nearby HKK to an extent as to notably impact the water balance by sublimation. Shenbin *et al*. (2006) analysed potential evaporation over 1961–2006 on the Tibetan Plateau in China, including two stations (WMO no. 51804, 3,091 m and no. 55228, 4,252 m) located in the vicinity of the Pakistani and Indian borders. Their analysis indicates a decreasing annual trend in potential evaporation between 40 and 20 mm per decade. This decrease in evaporation is corroborated by Khattak *et al*. (2011) and Forsythe *et al*. (2012), who extended an analysis on summer cooling over 1961–1999, initiated by Fowler & Archer (2006) to the 2005–2007 period. Findings support the hypothesis that decreasing summer temperatures potentially reduce energy available for evaporation.

To summarize, estimates of actual evaporation in recent literature on UIB water balance assessments are very few and uncertain. In the absence of *in-situ* observations on glaciers and snow-dominated areas, evaporation is ignored in several studies. For the same reason, absolute actual evaporation estimates remain highly uncertain, despite this variable constituting a crucial residual in the water balance. Few *in-situ* estimates on actual evaporation at high altitudes are provided for Siachen glacier and the Tianshan Glaciological Station. Estimates are in the same value range of 200±100 mm/yr. Reliable satellite-based estimates are unavailable since imagery serves non-glaciated or snow-covered areas. It is known that over high-altitude glaciated areas radiation can be very high, affecting latent heat fluxes. Although potential evaporation at high altitudes is likely some multiples higher than actual evaporation, actual evaporation is constrained by lack of evaporable water in the extensive arid parts of the UIB. Estimates by GCMs on potential evaporation in this study are in the range 750 ± 100 mm/yr. Sound correction to actual evaporation is not provided in the literature but, as indicated above, estimates require substantial reduction. Given the relative

large uncertainty, we revert to the actual evaporation estimate of 200 ± 100 mm/yr by Bhutiyani (1999) and Li & Ye (1998), which we consider the most reliable.

ICE STORAGE IMPLICATIONS

After quantifying the long-term averages and related uncertainties of the r.h.s. terms in the water balance Equation (1), the rate of change of water storage over the averaging period, $E[\mathrm{d}V/\mathrm{d}t]$, including its uncertainty, is unequivocally determined. As discussed in the section 'Basin mass balance', groundwater or surface water storage (reservoirs) are negligible in this region, and therefore the expected value of the derivative should reflect on the average total snow and ice storage change over the averaging period. Estimates on ice storage changes in the UIB are mostly indirect, and rely on gravimetric or geodetic assessments from satellites, combined with *in-situ* information primarily on the lower (debris covered) end of glaciers. An excellent review on the different methods to assess changes in glacier ice storage in relation to the water balance is provided by Gardelle *et al.* (2013). In the same work, changes on glacier water balance (1999–2011) for the Karakoram East and Karakoram West regions have been estimated by the geodetic method. These two regions correspond to the Hunza and Shigar/Shyok basins, respectively, for which declining or stable flow rates are observed. Results for both regions indicate accumulation at rates of 0.22 ± 0.14 m/yr and 0.3 ± 0.18 m/yr w.e. respectively. At lower elevation, in the glacier ablation zones, it is shown that the ice surface elevation slightly decreases at a rate of -0.33 ± 0.16 m/yr w.e. for the Karakoram region as a whole. Further, the study indicates overall positive storage changes of 0.09 ± 0.18 m/yr w.e. for Karakoram East and 0.11 ± 0.14 m/yr w.e. for Karakoram West. For the same region, Kääb *et al.* (2012) indicate a small decrease of -0.04 ± 0.04 m/yr water w.e. for the period 2003–2008. Although inverted glacier storage is indicated, differences are only (very) small, with large overlap when respective uncertainty ranges are considered. While these investigations, which we consider the most reliable to date, also suggest that ice storages may have declined in other areas within the UIB, such as in the Himalaya and the Hindukush ranges, they support the hypothesis of this study, that overall ice storage within the UIB may not have changed notably over the past decade, and that therefore the storage term in the water balance equation $E[\mathrm{d}V/\mathrm{d}t] \approx 0$.

DISCUSSION

The present analysis on the basis of hydrological water-balance considerations, provides a contribution to the discussion, whether changes in ice storage of the UIB have occurred during the first decade of the 21st century or longer, with possible implications for the long-term water supply to the downstream part of the Indus. From the trend analysis of 50-year basin outflow records, we have shown that an increase of the outflow volume, as one would expect in the case of a pronounced ice storage loss or negative value of $E[\mathrm{d}V/\mathrm{d}t]$, is not recognizable. Such loss is also not suggested by geodetic investigations by Kääb *et al.* (2012) and Gardelle *et al.* (2012a, 2013), who indicate that in the Karakoram range glacier ice storage has not notably changed, although it is suggested that increase in storage $(E[\mathrm{d}V/\mathrm{d}t] > 0)$ is more likely than loss over the past decade. This implies that net input $[P - ET]$ is going into storage instead of moving through the system. For the Hindukush and the Western Himalayas, which partly drain into the UIB, the ice storage change is indicated neutral $(E[\mathrm{d}V/\mathrm{d}t] \approx 0)$ to negative $(E[\mathrm{d}V/\mathrm{d}t] < 0)$. We see little rationale to question findings on ice storage that result from a number of different, independent estimation approaches.

For precipitation, we suggest an annual input of 675 mm ± 100 mm. This estimate results from the comparison of a number of independent data sources such as *in-situ* observations, satellite observations and GCMs. Estimates by *in-situ* observations and TRMM satellite cannot be used directly for the water balance as they require substantial upward correction. *In-situ* observations (mean of 438 mm/yr) are from a non-representative network of valley gauges. TRMM satellite estimates show unrealistic low precipitation (approximately 300 mm/yr), possibly caused by limitations of the infra-red and micro wave sensors to differentiate between liquid and solid precipitation. In the literature, it is reasoned that TRMM satellite estimates at very high altitude require at least doubling, to yield values higher than 600 m/yr. Combined results from uncorrected GCM outputs

indicate precipitation close to 700 mm/yr. Results from GCMs corrected for valley station observations indicate much lower values (approximately 300 m/yr) as one would expect, given that valley stations underestimate areal-average precipitation in the basin. Estimates by GCMs are very coarse ($\geq 0.5^{\circ} \times 0.5^{\circ}$), overlapping the landsurface, which features extreme topographic relief at much smaller scales and by itself influences spatial variability of precipitation. Although not addressed in the literature, GCM results may require local downscaling to also cover lower precipitation in dryer valleys, that make up a relatively small part of the UIB. A combination of these findings suggests a basin-average precipitation estimate of 675 ± 100 mm/yr.

In-situ estimates of actual evaporation at high altitudes are extremely few. For Siachen glacier (4,800 m, Nubra valley, eastern Karakoram, UIB) and for Tianshan Glaciological Station (3,545 m, Xinjiang Uygur Autonomous Region, Urumqi River Basin) *in-situ* estimates indicate actual evaporation in the value range 100 to 300 mm/yr or 200 ± 100 mm/yr. Results from alternative sources such as GCMs provide potential evaporation that is in the range 750 mm ± 100 mm. Sound correction to convert potential to actual evaporation is not provided in the literature, but it is obvious that estimates require substantial reduction.

Considering that: (1) the flow at Besham Quila has remained essentially stable over the last 50 years at about 460 mm/yr, (2) stable precipitation has been recorded over the same period (or longer) at the valley stations and (3) basin-average total precipitation (approximately 675 mm/yr) and potential evaporation calculated by GCMs have not notably changed since 1979, it is reasonable to assume that the expected value of the rate of storage change $\mathrm{d}V/\mathrm{d}t$ in Equation (1) has been close to zero ($E[\mathrm{d}V/\mathrm{d}t] \approx 0$) over the past decades, a finding suggested by various independent studies based on snow and glacier ice storage assessments only. When accounting for defined uncertainty ranges, the water balance of the UIB can be closed without implying significant overall ice storage change or unrealistic closure error, i.e., $E[P - ET - Q] \approx 0$ in Equation (1). The closure error is well within the uncertainty ranges of each balance term.

The first-order basin-average precipitation and evaporation estimates, which are based inter alia on long-term observations, provide also quantitative support that global data products used in other studies may be biased, and structurally underestimate precipitation as well as evaporation in the presence of extreme relief. In a recent study, Immerzeel *et al.* (2009) indicated an apparently ongoing loss of glacial ice in the Upper Indus of 1,980 km^3 at a (conservative) rate of 1%. This rate was explained by the gap between a 311 mm/yr TRMM precipitation and a modelled yield estimate of 360 mm/yr over 2001–2005, while evaporation was ignored. The supplementary streamflow is to be interpreted as annual glacier melt outflow in excess of 550 m^3/s, a quantity which is roughly 23% above the measured long-term annual steam flow at Besham Qila. Kääb *et al.* (2012) conclude that on the basis of their glacier storage imbalance estimates from 2003 to 2008, ongoing ice loss in the UIB should translate into an additional annual flow of 231 ± 46 m^3/s over that same period, approximately 10% of the recorded long-term mean. Bookhagen & Burbank (2010) derive a mean annual flow estimate of 4,200 m^3/s (644 mm/yr) for the Indus at Besham Qila from their large-scale hydrological modelling between 1998 and 2007, while their precipitation net of evaporation is less than 300 mm/yr. However, long-term observations contradict these figures, as the flow has actually fallen during the first decade of the 21st century by 4.5% below the 1961–2009 mean value of 2,380 m^3/s (approx. 460 mm/yr) (Table 2, Figure 2), making a significant reduction of ice storage over that period highly unlikely. Moreover, if one considers the observed increasing outflows in the sub-basins with nival regime (Sharif *et al.* 2013), such constitutes a positive contribution to the flow trend at Besham Qila.

Given the limited amount of population in the UIB (less than 1 million), which cannot take up this volume of excess water, and the absence of any larger hydraulic diversion structures, the estimated melt water excess flow, as suggested in some recent publications, is not recognizable in the observed stream outflow signal. We also note that old historical records in the Upper Indus provide indications that the annual yield has been higher between 1910 and 1965 than between 1869 and 1910 (Hewitt *et al.* 1989), suggesting that historically long-term yield fluctuations have indeed been registered, and are consistent with documented retreat of the Biafo glacier during that period. It is therefore plausible to infer from recorded outflow volumes, that the overall water storage in the basin, mainly snow pack

and glaciers, is at equilibrium since 1960, i.e., the storage derivative $dV/dt \approx 0$, or even slightly increasing, as possibly supported by Gardelle *et al.* (2012a, 2013) for the Eastern and Western Karakoram. As also pointed out by Schiermeier (2010) and Cogley (2012), the contrasting ice accumulation vs. reduction trends reported across the HKKH region as a whole, require additional investigation to confirm, if the overall water balance is indeed negative, or opposing ice storage trends may actually neutralize each other.

CONCLUSIONS

With reference to the introduction and the above analysis, the basic conclusions of this work can be summarized as follows:

- 50-Year observation records indicate that the stream outflow from the UIB, which hosts a substantial continental ice volume, has been essentially stable, or under statistically insignificant decline since 1960.
- Whereas seasonal variations in runoff in the UIB may well increase in the future (Barnett *et al.* 2005; Kaser *et al.* 2010; Savoskul & Smakhtin 2013), long-term annual yields do not show any signs of marked inflexion.
- Similarly, ground observations of precipitation and atmospheric reanalysis data show that the mean annual precipitation and potential evaporation has remained stable over several past decades.
- The analysis also shows that the annual precipitation over the basin is in the order of 675 ± 100 mm/yr, and thus at least double the estimates used in hydrological modelling studies of the UIB in the literature. Considering that actual evaporation is in the order of 200 ± 100 mm/yr and thus cannot be neglected, the hydrological mass balance of the basin can be closed without assuming ongoing glacier wastage.
- The above water resources analysis is supported by the most recent satellite altimetry investigations of glacier surfaces in the HKK (Hindukush–Karakoram), which indicate an overly stable ice volume for that particular region over the past decade.
- The uncertainty affecting the proposed estimates of precipitation and evaporation does not invalidate the central hypothesis of this paper, that a declining annual flow at the UIB outlet remains inconsistent with a significant shrinkage of glacial ice mass during the first decade of this century or longer.

Most importantly, we conclude that without addressing the future water demand side under changing socio-economic conditions (Archer *et al.* 2010), there is presently no evidence for a looming water crisis affecting the downstream part of the basin from a sole supply perspective. We recall however that a steadily growing water demand and demographic change within the Indus Basin puts Pakistan, with an annual per capita water availability of little more than 1,000 m^3 (UNESCO 2014), in the category of already highly stressed countries, with worse yet to come.

The present analysis also supports the conclusion by Bolch *et al.* (2012), that a poor understanding of the glacier water balance, in combination with the diversity of climatic conditions and the extreme topography, make future predictions on water resources availability in the HKKH difficult. The findings finally emphasize that the use of global data sets, especially in the case of precipitation and evaporation, without a broader verification against *in-situ* observations, may lead to unfounded and premature conclusions.

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