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Water availability on the Third Pole: A review

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ABSTRACT

The Third Pole is the headwater region for Asian major rivers providing water for millions of people inside and around. Driven by rainfall and snowfall with large spatial and temporal variation in their amount, water availability reviewed here is buffered by snow, glaciers, groundwater and springs. Most glaciers have been losing mass contributing to annual excess discharge. Significant depletions of groundwater and drying up of many springs are observed in some areas of the region. Summary of runoff components across the region shows rainfall is the major contributor, followed by snow and glacier melt, though their relative contribution varies among basins. Modelling studies project a changing seasonality of river runoff, increased extremes and a high variability among the river basins.

1. Introduction

The Third Pole is known as the fresh water tower of Asia [21,85]. Outside the polar regions, it has the highest concentration of snow and glaciers, with a glacial volume of about 7000 km^3 [23] and acts as a source region for large river systems in central, southern, and eastern Asia [64] (Fig. 1). Water from the snow and glaciers along with rainfall feed the major rivers originated on the Third Pole and water from these river basins fulfill the needs of drinking water, irrigation, energy, industry and sanitation for about 210 million people within the region and about 1.3 billion people downstream of the region [6].

Owing to recent changes in climate, the uncertainty about water availability is increasing in the region [49]. During the period of 1901 – 2014, the annual mean surface air temperature has increased by over 0.104 °C per decade, with most parts of the Third Pole experiencing a warming trend, especially the Tibetan Plateau [62]. Similarly, the trend of precipitation has also increased in the region, more rapidly since the mid – 1980's [62], though the interannual variability of precipitation is very complex with higher variability found in the central and western part on the Tibetan Plateau [47]. Increases in temperature and precipitation as well as changes in precipitation patterns, and accelerated melting of snow and glaciers all contribute to the increasing uncertainty in water availability of the region [22].

Many review studies have assessed the changes in climatic variables and their impact on water resources within the sub-regions of the Third Pole. Bibi et al. [9] assessed the recent climatic changes over the Tibetan Plateau and the responses of cryosphere, biosphere and hydrosphere. Similarly, Yang et al. [84] reviewed the changes in climatic variables on the Tibetan Plateau and then assessed the response of water and energy cycles to the changes in those variables. Cuo et al. [16] reviewed the changes in seasonal and long-term flow patterns of streamflow among different categories of rivers in the Tibetan Plateau and their responses to climate change and human activities. All these reviews have been conducted for a sub region of the Third Pole region and have focused on the past climate change and its impacts on the water resources. There is a clear need for a study focused on the impacts of climate change on both past and future water resources within the entire Third Pole region. In addition, groundwater and springs were seldomly mentioned in previous review studies. In this review, we have summarized some of the principal components of water resources in the Third Pole including rainfall and snowfall as primary drivers whereas glaciers, snow, springs and groundwater as the buffers and the impacts of current and future climate change on these water resources. In addition, this study also evaluates the adequacy of observations and uncertainty among future climate change projections.

2. Primary drivers of water availability

Precipitation is the primary driver of water availability in the Third Pole region. Precipitation generally has two forms namely rainfall

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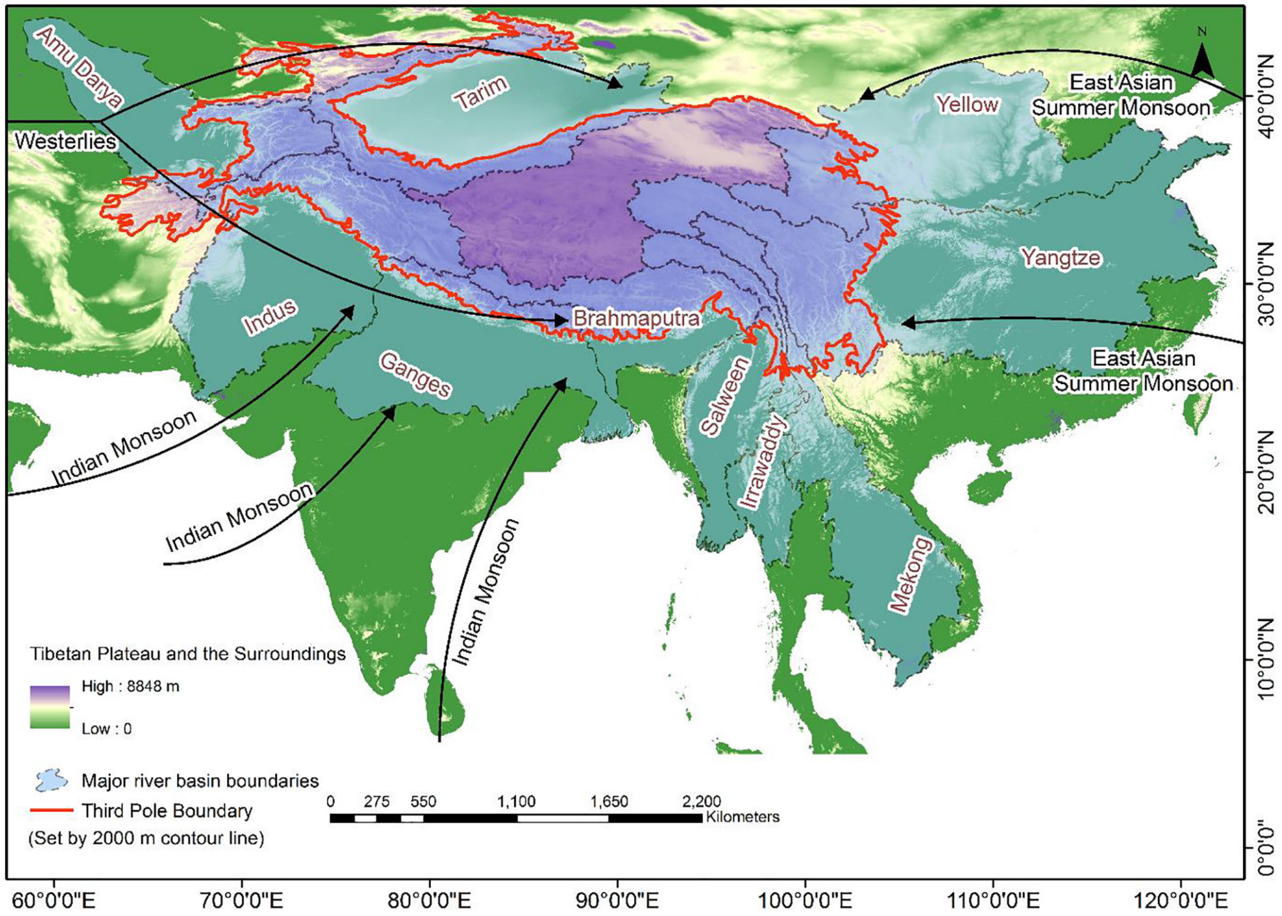

Fig. 1. Third pole region and the major river basins within it. 1. Tarim river basin (TA), 2. Upstream Amudarya river basin (UA), 3. Upstream Indus River basin (UI), 4. Upstream Ganges river basin (UG), 5. Upstream Brahmaputra river basin (UB), 6. Upstream Salween river basin (US), 7. Upstream Mekong river basin (UM), 8. Upstream Yangtze river basin (UY), and 9. Upstream Yellow river basin (UYE).

which is dominant at low elevation and snowfall at high elevation. It is hard to distinguish snowfall from rainfall due to limited observations of snowfall and it is also complex to estimate the threshold temperature for snow and rain accurately, which is considered to vary significantly among different climates within Northern Hemisphere [34]. Though rainfall is the key driver in most of the upper river basins on the Tibetan Plateau, snowfall is also an important component of the water cycle and may account for a large part of total precipitation in areas with high elevation and low temperatures [47]. Zhang et al. [88] found that the contribution of snowmelt was particularly higher than that of rainfall in Upper Indus, indicating that majority of precipitation there falls as snowfall rather than rainfall. In some mountainous areas of Tarim river basin, snowfall is also found to be the major form of precipitation [78].

Due to the difficulties mentioned above, the spatial and temporal analysis is generally conducted based on the total precipitation without distinguishing snow from rainfall. Processes affecting the precipitation are very complex resulting in its large spatial and temporal variation within the region caused by the interaction of local and large-scale circulation systems [74]. Within the Tibetan Plateau, precipitation shows a high spatial variability with a strong north-south gradient and east-west seasonality, caused due to orographic and climatic effects [25]. From the Tarim river basin in the northern Third Pole to the southeast Himalayan foothills, the precipitation was observed to vary from 50 to more than 6000 mm yr^{-1} [47]. In the eastern Himalaya, the majority of precipitation falls in between June and September because of the influence of Indian and East Asian Monsoon climate system. Compared to eastern parts, precipitation in western parts is much more uniformly distributed throughout the year due to the effects of the westerlies and southwesterly airflows [11]. On the central Tibetan Plateau, in the northeast Qilian mountains and in the Himalaya, most of the precipitation falls in summer months [47]. In the Karakoram region, about two thirds of the precipitation at high altitude occurs during the winter months [30] and half of it is attributed to the eastward propagating cyclones which provide winter precipitation to northwestern parts of the Indian subcontinent [7]. In the western and central Tibetan Plateau and in northwestern India, the interannual variability of precipitation is high whereas in the eastern and elevated parts, it is low. Within the whole Tibetan Plateau, precipitation shows a slightly decreasing trend during 1901 – 2014 whereas during 1961 – 2013, it shows a statistically significant increase and more rapid increase since the mid-1980s [62]. It should be noted that most meteorological stations are in the eastern and southern TP and very few stations are located at higher than 5000 m, the predictions of precipitation based on the limited observations may be somewhat biased. Thus, more in-situ hydrometeorological observations are needed in future.

3. Buffers in the hydrological system

3.1. Snow

Snow is an important water resource because snowmelt is an important contributor to discharge in the major upstream river basins of the Third Pole. The snow covered area varies significantly among different basins with the highest annual average snow coverage in Yangtze

Table 1
Overview table indicating the quantity of different components of water availability in different river basins of the Third Pole Region.

River basin	Components							
	Precipitation		Snow cover area		Glacier area		Glacier volume	
	Amounts (mm)	Reference	Amounts (km^2)	Reference	Amounts (km^2)	Reference	Amounts (km^3)	Reference
Tarim	116.8*	Chen et al., [15]	67,061 (15.9%)*	[28]	2310.26 (8.6%)*	Bajracharya et al., [5]	1631*	Farinotti et al. [23]
Amudarya	110*	Rakhmatullaev et al., [60]	9918 (1.6%)*		2566.18 (1.5%)*		731.39**	
Indus	346**	Lutz et al., [45]	167,992 (16.7%)*		15,061 (8.7%)**		2389**	
Brahmaputra	573**	Lutz et al., [45]	107,121 (20.4%)*		3105.75 (1.48%)**		598*	
Ganges	900**	Lutz et al., [45]	47,742 (4.8%)*		1627.08 (4.7%)**		494**	
Yangtze	333**	Zhang et al., [88]	193,304 (9.4%)*		1362 (0.4%)**		102**	
Salween	595**	Lutz et al. [45]	38,571 (10.7%)*		637.92 (0.8%)**		44**	
Mekong	642**	Lutz et al. [45]	23,534 (3%)*		179.85 (0.3%)**		8.96**	
Yellow	515**	Zhang et al., [88]	95,193 (9.4%)*		107.87 (0.1%)**		7.52**	

* Indicates whole river basin area.
** Indicates upstream river basin area.

river basin and lowest in Amudarya river basin (Table 1).

Although 59% of the Tibetan Plateau is covered with snow in winter [58], it shows a large variation in the seasonality of snow cover among the basins. In the upstream Indus basin, large parts are snow covered for prolonged periods during the year. Snow ablation peaks at the end of spring and snow accumulation starts in early winter [31]. For the Brahmaputra river basin, snow cover is at its maximum at the beginning of spring and is minimal in summer months [72]. For the upstream parts of the Amudarya and Ganges river basins, the maximum value of snow cover occurs in late winter after which snow ablation starts and minimum snow coverage is observed during summer [18,72]. For the upper Mekong and Yellow river basins, the snow cover is highest in winter months, with ablation starting in spring months and peaking in summer months [38]. In the upstream Salween river basin, the maximum value of snow cover occurs in the late autumn and ablation starts at the beginning of spring and peaking in summer months [42]. For upstream Yangtze river basin, highest snow cover occurs in mid-autumn whereas snow ablation starts sharply from late spring, peaking in summer [42].

3.2. Glaciers

Glaciers within the Third Pole are an important source of fresh water available in the region. Out of a total area of about 5 million km^2, glaciers cover a total area of about 98,000 km^2 and have a total volume of $7.0 \pm 1.8 \times 10^3$ km^3 [23]. Both the glacier coverage and glacier volumes in major river basins vary significantly from one to another with the highest amounts found in Indus (Table 1). Since 1970s, due to global warming, most of the glaciers of the Tibetan Plateau have been losing mass with a general reduction of 9% [85]. During 2000–2016, negative mass balances were observed for Brahmaputra, Indus, Ganges, Amudarya, Salween, Yangtze and Mekong with values ranging from about -0.09 to -5.1 Gt yr^{-1} leading to an annual excess discharge ranging from -163 ± 66 m^3/s^{-1} to -3 ± 2 m^3/s^{-1} whereas a positive mass balance for Tarim river basin was observed with a value of about 0.4 Gt yr^{-1} [12]. It should be noted that positive mass balances are observed in some areas including the inner Tibetan Plateau [87], central Karakoram and the western Pamir [26]. Increase in summer snowfall in Pamir, due to increase in irrigation intensity in lowlands of HMA, particularly in Tarim river basin could favor the increase in glacial growth in Pamir region [17]. Positive glacier mass balance in Karakoram may be attributed to increased winter precipitation [86] and the summer cooling [24]. These studies indicate the complex effects of climate as well as anthropogenic activities affecting the glaciers in the region.

3.3. Groundwater

Groundwater is a very important source of water in the lowlands of the Third Pole. It provides an important water resource for about 75% of the irrigated areas in South Asia [65]. In the Himalaya catchments, it acts as transient storage of water [20]. In the Third Pole, significant depletion of groundwater has been observed in Indian plains and adjacent regions [10]. In northwestern Indian states, satellite based estimates of groundwater depletion is 17.7 ± 4.5 km^3/yr during 2002–2008 [63]. There have been notable depletions in Nepal as well [19,54]. In most parts of the Third Pole, information about hydrogeological aspect of aquifers is mostly unknown. The studies that have been carried out are by characterizing aquifer systems or understanding about geological formation and hydrogeological characterstics in places such as Northeastern India [48,46], Northwestern India [50,41] and Nepal [69,35,54]. In the Tibetan Plateau, groundwater is considered mainly recharged by infiltration from snow or glacier melts at high elevations and could be crucial for sustaining baseflow and springs [27]. In central Nepal Himalaya, the contribution of groundwater is found to be even higher than snow and glacier melt [2]. Climate change can impact groundwater resources with the effects of precipitation or temperature changes on the recharging capability [70]. For example, the groundwater storages of the Tibetan Plateau are found to increase during 2003–2009 possibly due to increased snow/glacier melts and/or precipitation [82]. However, due to scarce observational data for groundwater, there are only a few model based studies which fully account for ground water processes in the region [2,50,59].

3.4. Springs

Springs serve as a primary source of water in majority of households in the Himalaya mountains due to the inaccessibility to water from major rivers flowing into deep valleys. For example, in the Indian Himalaya, springs provide water for about 64% of the total irrigated land [61]. Although precipitation is found to generally increase, springs are reported to be drying up in the region possibly due to the rather unstable rainfall pattern (such as the shorter duration of rainfall and a reduction in winter rainfall found in Sikkim), the increasing effects of human activity [61,77,71], or the perturbation caused by earthquake [56]. It is reported that many springs are drying up in the Himalaya watersheds [66] including the Indian Himalaya with nearly half of natural springs found to be drying up [3], the central Himalaya such as Nepal where ~12% of springs are observed to have dried up during the last 10 years [56] and the eastern Himalaya such as Sikkim where spring discharge has decreased by almost 35% in the 2000's [77]. However, due to the scarcity of data, the condition of most of the springs is yet unknown. Only a few studies have been carried out to establish the relationship between precipitation, spring discharge and recharge in small and distributed areas [52,80,77,79,67,40,55]. It is shown that there is large variation in the Third Pole. In the eastern part of the Third Pole, in Sikkim and Uttarakhand, rainfall and spring discharge are well correlated [77,1] whereas inverse patterns with monthly rainfall are also seen in western Himalaya such as Kashmir [51].

4. Runoff and its components

Different studies using different modeling methods, such as degree day [31,45,4] and energy balance methods [88], have been used to quantify the total runoff and its different components namely the glacial melt, snowmelt, rainfall and baseflow in different upstream river basins of the Third Pole region. Lutz et al. [45] used a high resolution cryospheric-hydrological model based on the degree day approach to assess the contributions of all the components of runoff in the major upstream river basins of the Tibetan Plateau. With an energy balance method for snow modelling and a degree day approach for simulating glacier melts (including snow melts on top of glacier), Zhang et al. [88] used the distributed hydrologic model VIC to assess the contributions of snowmelt, glacier melt and rainfall to runoff in different upstream river basins of the Tibetan Plateau. Recently, Armstrong et al. [4] have proposed a new method for differentiating snow on land, snow on glacier ice and exposed glacier ice by improving MODICE (MODIS Persistent Ice) method based on a "two-strike" classification of "ice-free" pixels in combination with the MODSCAG (MODIS Snow Covered-Area and Grain size) retrieval algorithm to create more accurate snow and glacier maps, and they used the improved snow and glacier cover data as input for a temperature index model to successfully obtain the contributions of snow and glacier melt in five major river basins of the Third Pole.

Based on studies by Armstrong et al. [4], Kamp and Pan [36], Lutz et al. [45] and Zhang et al. [88], and so on, which are representative across nine basins, a summary of total runoff components for each major basin as well as the whole region are provided in Table 2. Generally, rainfall runoff is the most important component for most of the major basins except the Indus, Amudarya and Tarim basins where snow or glacier melt seem to be dominant. It is obvious that the components and relative proportions of them can vary much for different basins. For example, in Brahmaputra river basin, although the annual snow coverage is around 20% of the total basin area, rainfall runoff dominates the total runoff [45,88] where monsoon season contributes to about 70% of annual total precipitation, which is also the main melt season for this basin, with wet downstream climate lowering the impact of meltwater contributions [32]. For the upstream major basins including Mekong, Salween, Yellow and Yangtze, the contribution of snowmelt is relatively moderate, with its contribution to total annual runoff mainly within 20 ~ 30% [45,88]. However, seasonal snowmelt can contribute greater than 50% in Amudarya [4,36] and Indus [4]. Such differences can be partly explained by their different snow coverage. Indus basin has very large snow coverage and its major part is covered with snow for prolonged periods of the year [31], whereas, for Ganges, Mekong, Salween, Yellow and Yangtze river basins, the annual snow coverage is less than or equal to ~10% of their respective basin area [28]. Similar to snowmelt, the importance of glacier melt also varies dramatically among the different basins. The Indus has the largest contribution to streamflow from glacial melt [31,45], with much lower contribution of the other major basins such as the Yellow, Yangtze, Mekong and Salween with reported contributions mostly less than 20% [68,88,29]. It has been indicated that the relative importance of glacier melt increases with proximity to the glaciers [45]. For example, glacial melt only contributes about 12% of total runoff in upstream Ganges river basin [45], but increases up to about 21% and 58% for Dudhkoshi and Langtang, respectively, which are both upstream, highly glacierized sub-basins of Ganges river [59]. It should be noted that due to the differences in basin definitions, study periods, modeling approaches, input and calibration data (observations), there are truly some differences in the discharge components reported by different literatures indicating a possibly large uncertainty in some basins. The most significant difference may be the snowmelt contributions of UI, UG and UB with the large standard derivations of ~44%, ~27% and ~35%, respectively, as shown in Table 2. For example, the snowmelt contributions in UI, UG and UB from Armstrong et al. [4] are all much larger than those from Lutz et al. [45]. It may be because of their different melt modelling subroutines and different discharge observations. Armstrong et al. [4] used improved snow and glacier cover data as input for snow/glacier melt modelling and Lutz et al. [45] calibrated their model using more upstream gauge stations.

5. Climate change impacts

It has been indicated that most parts of the Third Pole have undergone a significant warming trend. In regions such as the Tibetan Plateau, precipitation shows an increasing trend after the 1980s. Due to these trends in the climatic variables, there will be more uncertainty and variability in the hydrological cycle of the region. Such complexity is reflected in the glacier response during the last several decades with the most intense glacier retreat occurring in the monsoon dominated region, less retreat in the transition region and the least retreat in the westerlies dominated region [85]. Future climate projections under different RCP scenarios also show negative mass balance and lower equilibrium line altitudes by the end of the century for the Himalayan region, with some percentage of glaciers facing eventual disappearance [14]. Rise of global temperatures by 1.5 °C will lead to a decrease of around 36% of total glacial mass stored in the High Mountain Asia [39]. Changes in climatic conditions in winter westerlies have been linked with increases in snow water equivalent (SWE) in Indus and Ganges catchments, resulting in more snowfall in parts of Indus [13,76,53]. In High Mountain Asia, increased temperature [85] causes an earlier melting of snow [73] and more precipitation falls in the form of rain in the majority of the region [45,37] and this results in negative summer SWE trends in the region. Along with projections of increasing temperatures, total precipitation also shows an increasing trend by the middle of twenty-first century [37]. Due to these ongoing and projected changes in glacier and snow coverage and projected precipitation trends, the timing of water availability may change and this could pose challenges for water management. Although the total water availability may only increase, the challenge is to deal with shifts in timing and an increase in extremes.

Several modelling studies have been conducted to evaluate the impacts of climate change on future water resources. Immerzeel et al. [32] used a glacio-hydrological model for projecting runoff at the end of the century for Baltoro and Langtang catchments. In spite of their different climates, it was indicated that both catchments showed a consistent increase in total streamflow, with projected glacial melt increase expected to be main cause for streamflow increase in Baltoro, and projected precipitation increase expected to be main cause for streamflow increase in Langtang catchment. This study concluded that

Table 2
Summary of definition, runoff components and their percentage contribution for the nine major river basins from different literatures.

River basin	Location	Basin Area (km^2)	Time	Modeling approach	Total flow (km3)	Glaciermelt (km^3)	Snowmelt (km^3)	Rainfall (km^3)	Reference
Indus	UI	200,677	2001–2005	Degree day	62.4	19.9 (32%)	24.9 (40%)	17.5 (28%)	[33]
	UI	402,314.40	1998–2007	Degree day	230.9	93.7(40.6%)	50.4(21.8%)	61.9(26.8%)	[45]
	UI	349,972	2001–2014	Degree day	323.8	9.1(3%)	238.4(73%)	76.3(23%)	[4]
Amudarya	UA	81,794	2013	Degree day	38.7	9.3(25%)	29.4(75%)	NA	[36]
	UA	451,074	2001–2014	Degree day	86.9	10.3(12%)	56.4(65%)	20.2(23%)	[4]
Tarim	WRB	1,020,000	1961–2006	Degree day	34.7	14.5 (41.5%)	NA	NA	[83]
	UT	115,551	1966–1995	Degree day	17.1	6.1(35.8%)	9.9(58.2%)	NA	[43]
Ganges	UG	138,644	1998–2007	Degree Day	150.8	17.4(11.5%)	13.0(8.6%)	99.6(66.0%)	[45]
	UG	123,483	2001–2014	Degree Day	174.4	1.6(1.0%)	81.1(47.0%)	91.7(52%)	[4]
Brahmaputra	UB	344,977	2001–2014	Degree day	642.3	7.4 (1.0%)	467.3(73.0%)	167.6 (26.0%)	[4]
	UB	357,542	1998–2007	Degree day	247.1	39.3(15.9%)	22.2(9.0%)	145.5(58.9%)	[45]
	UB	201,200	1961–1999	Energy balance*	58.2	6.8 (11.6%)	13.4(23.0%)	38.1(65.4%)	[88]
Salween	US	67,740	1980–1985	Energy balance*	21.4	1.1 (4.8%)	4.4 (20.4%)	15.9 (74.8%)	[88]
	US	NA	1998–2007	Degree day	32.5	2.7 (8.3%)	8.9 (27.5%)	13.7 (42.0%)	[45]
Mekong	UM	NA	1998–2007	Degree day	24.9	0.2 (0.9%)	8.1(32.5%)	10.9(43.9%)	[45]
	UM	53,800	1961–2000	Energy balance*	14.9	0.2 (1.4%)	3.1(20.9%)	11.6 (77.7%)	[88]
Yangtze	UY	137,704	1961–2000	Degree day	17.8	1.9 (11.0%)	NA	NA	[68]
	UY	137,704	1963–2005	Energy balance*	12.7	0.8 (6.5%)	2.8 (22.2%)	9.1 (71.3%)	[88]
	UY	139,000	2003–2014	Degree day	17.6	0.9 (5.2%)	1.2 (6.6%)	NA	[29]
Yellow	UYE	121,972	1961–1999	Energy balance*	21.1	0.2 (0.8%)	4.8 (22.4%)	16.2 (76.8%)	[88]

Note: UI = Upper Indus, UA = Upper Amudarya, UG = Upper Ganges, UB = Upper Brahmaputra, US = Upper Salween, UM = Upper Mekong, UY = Upper Yangtze, UYE = Upper Yellow, UT – Upstream Tarim, WRB = Whole river basin, NA = Not available.

* Zhang et al. [88] used energy balance method for snow melt modelling but degree day method for calculating glacier melt.

water availability in this century was very less likely to decline and river basins depending on glacier melt and monsoon rainfall would continue to meet the expected increase in water demands within vulnerable river basins such as Indus. Lutz et al. [44] had analyzed the changes in seasonality and hydrological extremes in the upper Indus Basin. Predictions for seasonality of flow included minor increases in summer flow and increased flow in other seasons in near future period of 2021–2050, and decreases in summer flow and stronger increased flow in other seasons for far future period of 2071–2100. Mainly driven by increases in extreme precipitation, increase in flooding events during 21st century due to increases in intensity and frequency of extreme discharges were predicted for most of the upper Indus basin. Their study suggested developing sound basin-wide adaption strategies that could take into account changing demand and supply in the Indus basin. Similarly, Wijngaard et al. [81] had assessed the future changes in climatic extremes and hydrological extremes for the upper Indus, upper Ganges and upper Brahmaputra river basins and found out that climatic extremes were projected to increase in magnitude by end of 21st century, with precipitation extremes increasing mostly in upper Indus basin. In rainfall dominated upper Brahmaputra river basin, increases in precipitation extremes may contribute to discharge extremes. Such studies have also been conducted in Lhasa River [57], Koshi [8] and Shigar [75] watersheds which generally project an increase in runoff. However, the rather big uncertainty from the evidently different outputs of different climate models is still a large problem in future projection studies as indicated by Immerzeel et al. [32].

6. Conclusion

Due to complexity of processes affecting precipitation, there is large spatial and temporal variability in the region. Two forms of precipitation on the Third Pole namely the snowfall and rainfall also add to the variability. Seasonality of snow cover shows a large variation among different river basins with maximum snow cover varying from early spring (e.g. Brahmaputra), mid-autumn (e.g. upstream Yangtze), late autumn (e.g. upstream Salween) to winter (e.g. upper Mekong, Yellow, Amudarya and Ganges). Many glaciers have been losing mass in the region contributing to annual excess river discharge within the river basins where the glaciers are situated. Significant depletion of groundwater has been observed in the Indian plains and Nepal. The lack of sufficient observational data has led to an inadequate understanding of groundwater hydrology in the region. Many springs are reported to be drying up or becoming seasonal in the region. However, due to the lack of observational data, the condition of most of the springs is still unknown.

The summary of hydrological modeling studies indicates that for all the river basins, cumulatively, rainfall is the main contributor to runoff followed by snow and glacial melt. The relative contribution of these components, however, varies greatly among the different river basins. Due to the increase in precipitation and glacial melt, near future water availability is generally projected to increase for various river basins and sub-basins, with also clear seasonal shifts in some basins. Hydrological and climatic extremes were also predicted to increase in some river basins, with increase in precipitation extremes causing an increase in discharge extremes. However, there is large uncertainty in these future projections owing to climate model uncertainty.

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