IWMI Research Report

150

Glacier Systems and Seasonal Snow Cover in Six Major Asian River Basins: Hydrological Role under Changing Climate

Oxana S. Savoskul and Vladimir Smakhtin

IWMI International Water Management Institute

CGIAR RESEARCH PROGRAM ON Water, Land and Ecosystems

CGIAR RESEARCH PROGRAM ON Climate Change, Agriculture and Food Security CCAFS

Research Reports

The publications in this series cover a wide range of subjects—from computer modeling to experience with water user associations—and vary in content from directly applicable research to more basic studies, on which applied work ultimately depends. Some research reports are narrowly focused, analytical and detailed empirical studies; others are wide-ranging and synthetic overviews of generic problems.

Although most of the reports are published by IWMI staff and their collaborators, we welcome contributions from others. Each report is reviewed internally by IWMI staff, and by external reviewers. The reports are published and distributed both in hard copy and electronically (www.iwmi.org) and where possible all data and analyses will be available as separate downloadable files. Reports may be copied freely and cited with due acknowledgment.

About IWMI

IWMI's mission is to improve the management of land and water resources for food, livelihoods and the environment. In serving this mission, IWMI concentrates on the integration of policies, technologies and management systems to achieve workable solutions to real problems—practical, relevant results in the field of irrigation and water and land resources.

IWMI Research Report 150

Glacier Systems and Seasonal Snow Cover in Six Major Asian River Basins: Hydrological Role under Changing Climate

Oxana S. Savoskul and Vladimir Smakhtin

International Water Management Institute (IWMI)
P O Box 2075, Colombo, Sri Lanka

The authors: Oxana S. Savoskul is a Research Associate at the International Water Management Institute (IWMI) in Colombo, Sri Lanka; and Vladimir Smakhtin is Theme Leader - Water Availability and Access at IWMI in Colombo, Sri Lanka.

Savoskul, O. S.; Smakhtin, V. 2013. *Glacier systems and seasonal snow cover in six major Asian river basins: hydrological role under changing climate.* Colombo, Sri Lanka: International Water Management Institute (IWMI). 53p. (IWMI Research Report 150). doi:10.5337/2013.204

/ glaciers / runoff / snowmelt / snow cover / melt water / assessment / seasonal variation / water resources / groundwater recharge / aquifers / river basins / catchment areas / flow discharge / hydrological cycle / climate change / precipitation / simulation models / Asia /

ISSN 1026-0862
ISBN 978-92-9090-769-5

Front cover photograph taken in 2011 at the headwaters of the Syr Darya River shows Tekeshsay stream originating from Tekesh Glacier (*photo credit*: Maxim Petrov, Institute of Geology, Tashkent, Uzbekistan).

Please send inquiries and comments to IWMI-Publications@cgiar.org

A free copy of this publication can be downloaded at
www.iwmi.org/Publications/IWMI_Research_Reports/index.aspx

Acknowledgments

The authors gratefully acknowledge the help of Prasanna Sambandamurthy, Yamuna Udumalagala and Giriraj Amarnath (all of IWMI, Colombo), as well as Lynn Lay (Goldthwait Polar Library, The Ohio State University, USA) and Elena Shevnina (Saint Petersburg State University, Russia) during the search for published literature and in primary data acquisition, or both. Online resources of National Snow and Ice Data Center (NSIDC), World Glacier Monitoring Service (WGMS) and International Centre for Integrated Mountain Development (ICIMOD) were extensively used, and Graham Cogley (Trent University, Canada) is thanked, in particular, for sharing the dataset of the World Glacier Inventory - Extended Format (WGI-XF). The assistance of Ameer Rajah, Ranjith Alankara and Salman Siddiqui (all of IWMI, Colombo) was essential in downloading and processing data on seasonal snow.

The authors would also like to thank Victor Zagorodnov (Byrd Polar Research Center, USA), Andrey Yakovlev and Maxim Petrov (Tashkent State University, Uzbekistan), and Kenji Matsuura (University of Delaware, USA) for many fruitful discussions and valuable advice.

Constructive comments and criticism of two anonymous reviewers and Peter McCornick (IWMI, Colombo) are gratefully acknowledged.

Donors

This research study was funded by the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).

CGIAR — RESEARCH PROGRAM ON Climate Change, Agriculture and Food Security — CCAFS

The CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) is a strategic partnership of the CGIAR and the Earth System Science Partnership (ESSP). CGIAR is a global research partnership for a food secure future.

Contents

Summary

The hydrological role of the meltwater resources in the Indus, Ganges, Brahmaputra, Syr Darya, Amu Darya and Mekong river basins is, for the first time, comprehensively assessed at the basin scale. The states of the meltwater resources in the baseline (1961-1990) and current (2001-2010) periods are analyzed using the following characteristics: specific glacier runoff (average depth of annual discharge from glacier-covered area), basin total glacier runoff, shares of renewable and nonrenewable components in glacier runoff, total seasonal surface snowmelt from non-glaciated areas, portion of seasonal snowmelt lost for the recharge of groundwater aquifers, the contribution of glacier runoff and seasonal snowmelt to mean annual flow (MAF). The report presents a critical review of relevant publications and assessment of methods and data availability, compatibility, accuracy ranges and suitability for basin-scale studies. The evaluation of meltwater components is based on a wide range of data compiled from published sources: glacier mass budget items, rates of glacier mass balance, areal extent and total volume of glaciers and seasonal snow, terrestrial water budgets, and recharge rates of groundwater aquifers. Glacier runoff is evaluated using a semi-distributed model developed for this study. The evaluation of seasonal snowmelt is based on the published outcomes of a fully distributed model. It is demonstrated that glaciers and seasonal snow play a negligible role as contributors to MAF in the Mekong Basin (<1%) and an insignificant role in the Ganges and Brahmaputra basins (7% and 3%, respectively). In the Indus Basin, meltwater contributes around 35-40% to the total flow with seasonal snowmelt and glacier runoff shares being approximately equal. In the Amu Darya and Syr Darya basins, meltwater resources contribute 69% and 79%, respectively, to mean annual streamflow, and the share of seasonal snowmelt by far outweighs that of glaciers. From 1961-1990 to 2001-2010, the total values of meltwater components decreased by 6-25% in all the basins, apart from Mekong where snowmelt increased by 30% due to a slight increase in the snow cover extent. Meltwater contribution to annual flow decreased at the same time by 5% in the Indus and Amu Darya basins and by 20% in the Syr Darya Basin. In other study basins, contribution of meltwater to flow changed by less than 0.5%. The most pronounced change occurred in the composition of glacier runoff: the share of the nonrenewable component in the total glacier runoff increased from 16-30% to 26-46% in all study basins. At the same time, the share of the renewable component decreased more significantly due to the overall reduction of glacier-covered areas. As a result, total contribution of glacier runoff to MAF decreased in all study basins. It is shown that, future reduction of glaciers and seasonal snow cover due to climate change (CC) will mainly affect the seasonality of river flow and only marginally impact MAF in the Indus, Amu Darya and Syr Darya basins. In the Ganges, Brahmaputra and Mekong basins, future changes in glacier and seasonal snow extent will have little effect on hydrological regime altogether.

Glacier Systems and Seasonal Snow Cover in Six Major Asian River Basins: Hydrological Role under Changing Climate

Oxana S. Savoskul and Vladimir Smakhtin

Introduction

There is a widespread concern that glacier and seasonal snow areal reduction in High Asia will have adverse effects on food security of billions of people who depend on freshwater supplies from glacier and snow-fed rivers (Jowit 2008; UNEP 2009; Raina 2009; Hasnain 2009; Viviroli et al. 2011; Immerzeel et al. 2010). However, the scientific basis for this alarm remains obscure, since how much water glaciers and seasonal snow from non-glaciated areas do actually contribute to MAF in major Asian river basins at present, and to what extent this contribution might be affected by CC is largely unknown. At the current state of knowledge it is virtually impossible to find in peer-reviewed sources any certain and well-grounded statements on the amount of glacier and snowmelt water discharge in basins of the major Asian rivers. The publications dealing with the basin-wide assessment of glacier and snow contribution to river flow (Singh et al. 1997, 2008; Singh and Jain 2003; Dyurgerov et al. 1995; Shetinnikov 1998; Xu et al. 2007; Barnett et al. 2005; Hannah et al. 2005; Eriksson et al. 2009; Immerzeel et al. 2009, 2010; Sorg et al. 2012) are few, and most of them are either limited to just one basin, or do not distinguish between meltwater discharge from glaciers and seasonal snow, or both. Besides, the most common methods used for evaluation of meltwater discharge are hardly suited for basin-scale studies (Armstrong 2010; Viviroli et al. 2011). The terminology and basic concepts are either underdeveloped or there is no common understanding of what is meant by glacier runoff and snowmelt. This, together with the lack of commonly accepted reporting standards, results in confusion regarding how meltwater resources are accounted for. Another major knowledge gap is lack of differentiation between renewable and nonrenewable components of glacier runoff. Also, absence of reliable reference lines for describing recent and current state of glacier runoff and seasonal snowmelt in Asian basins hampers assessments of future changes in the meltwater resources under CC.

The scope of this report is to provide a comprehensive assessment of the hydrological role of glaciers and seasonal snow, with a focus on changes that have occurred over the past 50 years, and possible future changes under CC. The basins considered are Indus, Ganges, Brahmaputra, Amu Darya, Syr Darya and Mekong (Figure 1; Table 1). To achieve this goal, the report aims to: i) critically review the relevant literature with a focus on suitability and reliability of available methods and published data for basin-scale assessments of glacier runoff and seasonal snowmelt; ii) evaluate, in a methodologically coherent way across all study basins, meltwater components of river flow for two periods, 1961-1990 and 2001-2010, in order to analyze the impacts of recent CC on meltwater resources and to provide reference lines for future modeling of meltwater-related aspects of hydrological regimes and water availability in the study basins; and iii) critically review the current state-of-the-art knowledge in the field of modeling CC impacts on meltwater components of MAF, in order to identify currently existing knowledge gaps and to draw conclusions on the most likely changes of the future hydrological regimes due to changes in the meltwater components.

FIGURE 1. Map showing the boundaries of the study basins (red line), state borders (light yellow line) and snow-covered high-altitude belts where glaciers are located (white spots). At this resolution, individual glaciers cannot be distinguished from snow cover.

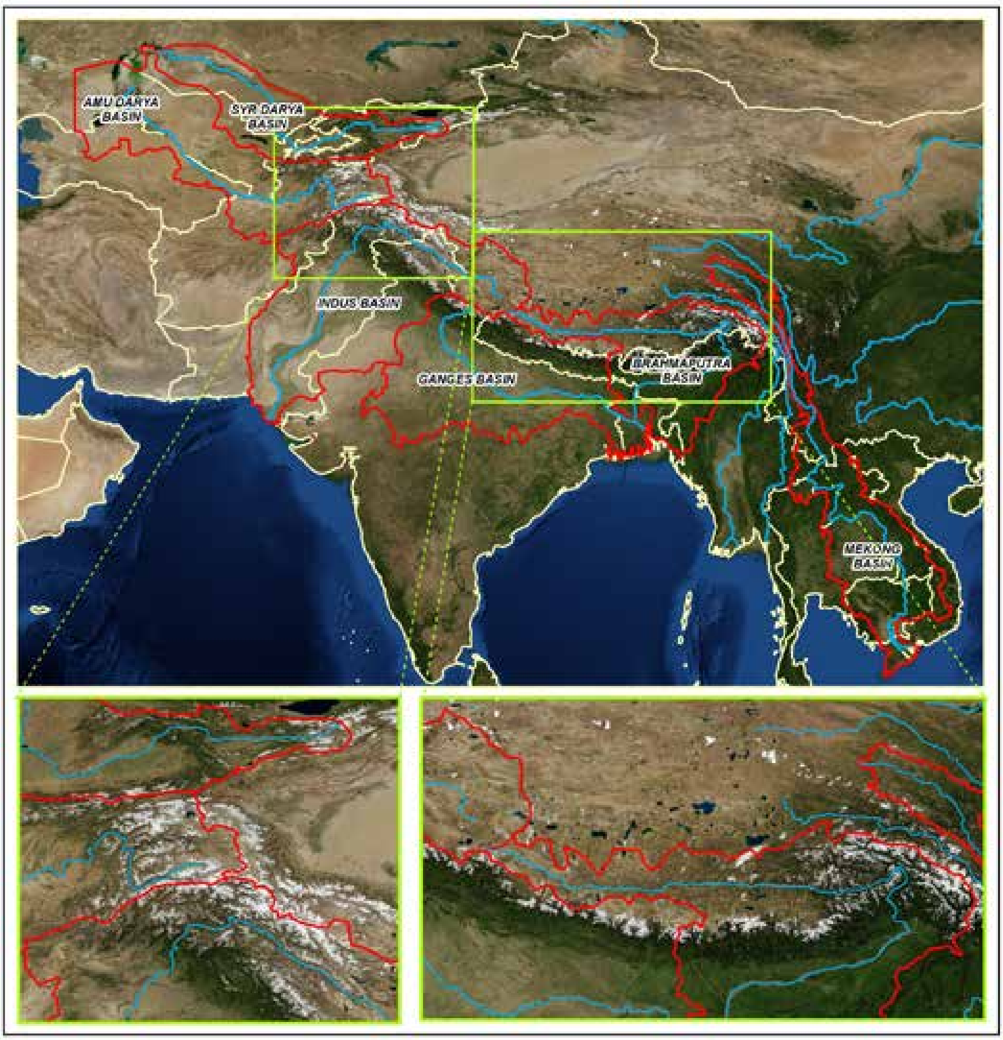


TABLE 1. Study basins, basic information.

Basin	Area (km^2)	MAF (km^3)
INDUS	1,207,100	235
GANGES	1,032,690	445
BRAHMAPUTRA	673,540	687
AMU DARYA	796,250	79
SYR DARYA	402,760	39
MEKONG	807,360	466

Data sources: AQUASTAT database of the Food and Agriculture Organization of the United Nations (FAO) (http://www.fao.org/nr/water/aquastat/main/index.stm); United Nations Environment Programme (UNEP) Global Environment Outlook (GEO) data portal (http://geodata.grid.unep.ch/).

Terminology and Basic Concepts

Estimation of glacier runoff is one of the mainstream themes in glaciology and mountain hydrology (Aizen and Loktionova 1996; Aizen and Aizen 1996, 1998; Ye et al. 2003; Hock et al. 2005; Thayyen et al. 2007; Zhang et al. 2007; Yao et al. 2007; Kang et al. 2009; Braun et al. 2009; Jost et al. 2012). Yet, there is hardly a common understanding of what is meant under 'glacier runoff', since broadly similar terms are currently in use to denote discharge from glaciers per se and that from glaciated catchments (i.e., catchments where glaciers are present, but cover just part of the terrain). Mayer et al. (2006) regard glacier runoff as flow from a highly glaciated catchment, which implies that the seasonal snowmelt from the ice-free rocky slopes in glacier surroundings also counts as glacier runoff. Kumar et al. (2010) and Singh et al. (2008) understand glacier contribution in the same way as runoff from the entire glaciated catchment but subtract the contribution from rainfall. Bocchiola et al. (2011) differentiate between 'glacier melt' and 'snowmelt' with an implication that seasonal snowmelt from ice-covered area does not count as glacier meltwater. Alford et al. (2009) too estimate glacier runoff as ice melt, and limit their assessment to the altitude belt of 4,000–6,000 m. In many other cases, 'meltwater' contribution from glaciated basins is evaluated without any distinction between 'glacier-melt' and 'snowmelt-derived runoff' (Young and Hewitt 1990; Singh et al. 1997; Singh and Jain 2002; Thayyen et al. 2007; Kumar et al. 2010; Immerzeel et al. 2010; Mukhopadhyay and Dutta 2010; Forsythe et al. 2010; Liu et al. 1999; Xu et al. 2007). To avoid confusion, it is recommended that the terms adopted in any future glacio-hydrological study are explicitly defined.

In this report, 'glacier' is defined as a natural ice body made out of snow consolidated under its own weight and large enough to 'flow' under gravity either in a spreading pattern from an elevated center towards the edges (dome-shaped ice sheets and ice caps), or downward (mountain glaciers). Glaciers have natural water storage capacity on an intra- and inter-annual scale. Part of the snow that accumulates on the glacier surface is released into the hydrosphere annually during the warmer part of the year, and the other part, which gets trapped and transformed into ice, melts with a delay of several decades and even centuries. The term 'glacier runoff' is defined here as a discharge from ice-covered area irrespective of its source (ice melt, snowmelt or rainwater). The two principal contributors to glacier runoff are ice melt and snowmelt. In the long run, the respective shares from those two sources vary from place to place in a range of 30-70% of total glacier runoff, according to the field investigations (Dyurgerov et al. 1995; Aizen and Aizen 1996; Lebedeva 1997; Shetinnikov 1998; Bocchiola et al. 2011). Rain contribution to glacier runoff is negligible. Even in Himalaya, where summer precipitation is abundant, rain falling on glacier surface adds a maximum of 2-3% to the entire discharge from glaciers (Kumar et al. 2010; Singh and Jain 2003; Singh et al. 2008).

The understanding of the term 'glacier runoff' here is based on the concept of glacier 'mass budget' (Hambrey and Alean 2004; Benn and Evans 2006), consideration of which allows glacier runoff to be calculated bypassing simulation of the complex processes within a glacier, such as snow consolidation, melting of snow and ice across glacier surface, inside glacier and beneath it. Glacier mass budget equation may be expressed as:

$$MB = P + C - GR - S \qquad (1)$$

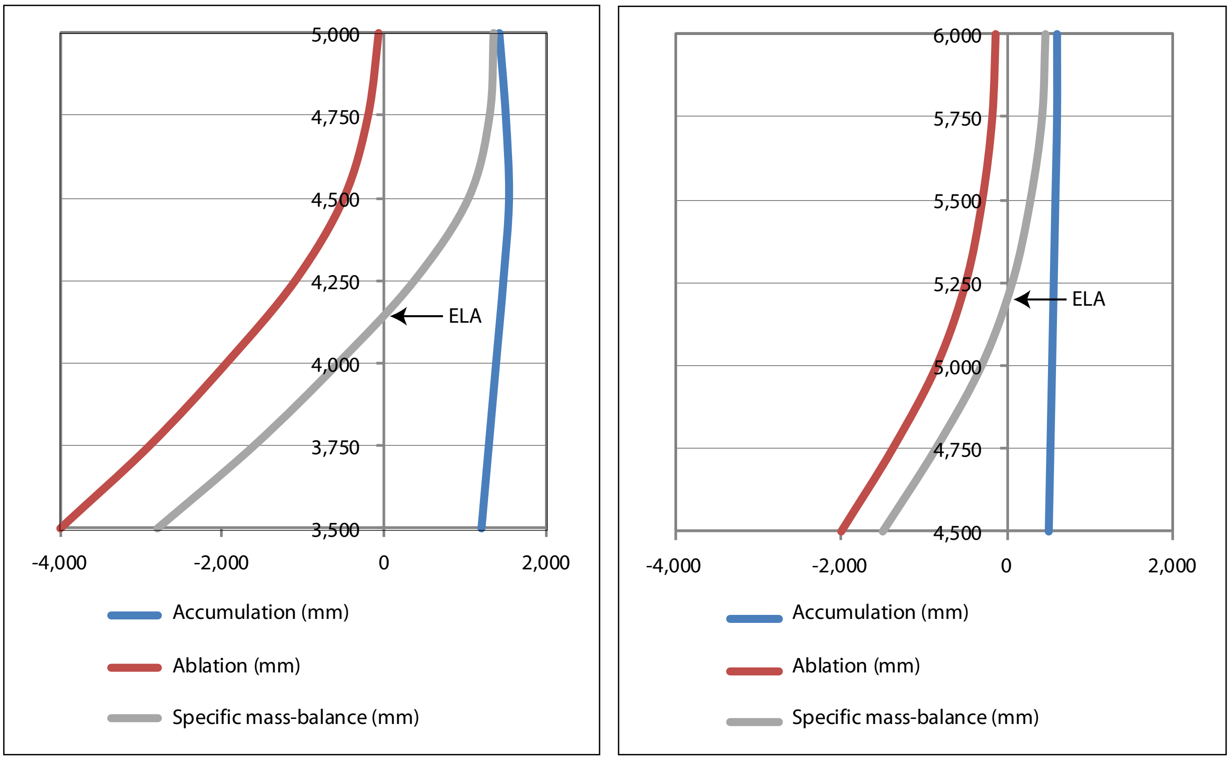
where: MB – net annual mass balance of a glacier; P – precipitation, the major item of glacier mass gain, i.e., accumulation; C – condensation, direct transformation of water vapor to ice, minor item of accumulation; GR – glacier runoff, the major item of glacier mass loss, i.e., ablation; and S – sublimation, direct transformation of ice to water vapor, minor item of glacier ablation.

The term 'specific' is used in this report to indicate an average depth of glacier ablation, accumulation or runoff with respect to the glacier area, i.e., net annual value of the relevant parameter divided by the total glacier area, measured in millimeters of water equivalent (mm w.e.).

Figure 2 illustrates typical altitude-dependency curves of principal glacier mass budget items (i.e., accumulation and ablation) under steady climate conditions, when they counterbalance each other in the long term (i.e., MB = 0). This graph helps to explain the meaning of common glaciological terms used in this report. The equilibrium line altitude (ELA) is an elevation, where mass-balance equals zero. The part of a glacier located above the ELA is the 'accumulation area'. In the annual cycle the net accumulation above the ELA is greater than net ablation. Part of a glacier located beneath the ELA is termed the 'ablation area', because here the net ablation prevails over net accumulation. The characteristic feature of the mass-balance altitude curve is the decrease from positive to negative values with increasing altitude. The term 'glacier regime' is used to describe steady state-specific accumulation (= ablation) values at ELA and to quantify the rate of glacier mass turnover. Active regime means high mass turnover, with specific accumulation/ablation at ELA above 1,500 mm; slow glacier mass turnover and regime occurs if specific accumulation/ablation at ELA are below 500 mm (Benn and Evans 2006; Kotlyakov 1997).

Glacier regime differs a lot depending on the regional climate. Where precipitation is abundant (periphery of mountain systems), glaciers can endure warm summers and maintain a 'lavish lifestyle' in terms of 'income' (accumulation) and 'expenditures' (ablation). In arid environments (interior parts of mountain systems), glacier mass exchange with environment is less active: they just 'barely survive' under limited precipitation and, therefore, lower temperatures are needed to sustain them. Since C and S (Equation 1) are minor items of glacier mass budget, typically not exceeding 150 mm (Kotlyakov 1997), precipitation (P) can be used as a proxy for glacier runoff

FIGURE 2. Schematic altitude-dependency curves of principal glacier mass budget items of a steady-state glacier under different climates. The altitude where mass-balance curve crosses Y-axis, i.e., accumulation equals ablation, is ELA. Specific glacier runoff (the major item of ablation) is expected to be greater in humid climate (left graph) than in arid conditions (right graph), because specific accumulation/ablation values are higher in areas with higher precipitation.



under steady state conditions. The implication is that the specific values of glacier runoff in cold and dry climate, e.g., in the Tibetan Plateau, are expected to be significantly lower than in humid and relatively warm conditions, e.g., in the south-facing Himalaya slopes. A combination of high precipitation with cold air temperature, e.g., in the Karakoram Mountains, is especially favorable for glacier existence, and results in active glacier regime and high specific runoff too.

To introduce the concept of the 'renewable' and 'nonrenewable components' of glacier runoff, glacier mass budget under steady climate should be compared with mass budget under consistent warming. In the first case, MB=0, therefore, runoff from a glacier in a steady state (GR_{SS}) based on Equation 1 can be expressed as:

$$GR_{SS} = P + C - S \quad (2)$$

GR_{SS} is a 'renewable water resource', since the amount of water lost annually by a steady-state glacier through runoff and sublimation is replaced by the net annual accumulation.

Runoff from a non-steady state glacier (GR_{NSS}) with imbalanced mass budget can be expressed as:

$$GRN_{SS} = P + C - S - MB \quad (3)$$

A consistently growing glacier has MB>0, which means that it stores more water than it releases. Under recent global warming most glaciers in the world have got a negative mass-balance (MB<0), which means that they produce more water than they receive. Thus, the absolute |MB| value of a glacier with consistent mass loss makes a 'nonrenewable resource', since it draws water from perennial glacier ice storage, which is not replaced by annual accumulation. Accordingly, GR_{NSS} of a retreating glacier may be conceptualized as a sum of 'renewable' (GR_{SS}) and 'nonrenewable' (|MB|) components:

$$GRN_{SS} = GR_{SS} + |MB| \quad (4)$$

The seasonality of glacier runoff is determined by the duration of the ablation season. Glacier runoff contributes to river flow for 2-3, maximum 4 months, mainly from early/mid-summer, till late summer/early fall and reaches its maximum in the Northern hemisphere in July-August. Glaciers' total mass significantly exceeds their annual mass turnover, meaning a very high water storage capacity, which allows them to smooth inter-annual flow variability, reducing risks of the late summer droughts in hot and dry summers (Hambrey and Alean 2004; Bolch et al. 2012). CC, however, may lead to consistent mass gain or loss in glaciers, thus increasing or reducing their inter-annual storage capacity.

Snow that falls on glaciers partly melts within one annual cycle, together with ice melt forming glacier runoff, and partly accumulates over a course of several years gradually consolidating and transforming into ice. Snow, which lasts over several years on an ice-free terrain, forms 'perennial snow fields' or 'packs', normally the first few meters and less in thickness. Outside of glaciated areas, where conditions for perennial snow accumulation are lacking, snow occurring in the colder part of a year forms a stable 'seasonal cover'. Contrary to glaciers, the cycle of seasonal snow mass turnover falls almost entirely within one year, with minor inter-annual fluctuations (Jansson et al. 2003). Therefore, seasonal snow has a negligible inter-annual storage capacity. Seasonal snow extends over significantly larger areas compared to glaciers, since it may form at much lower elevations. The intra-annual storage capacity of seasonal snow as a rule exceeds that of glaciers (Savoskul and Smakhtin 2013). The seasonality of snowmelt differs from that of glaciers in two important aspects: duration and timing. Seasonal snowmelt contributes to a flow typically over half a year or more and starts several months earlier than glacier ablation. The snowmelt period is more stretched in time, because snowmelt comes from a wider range of elevation bands, each one with its own seasonal peak that gradually shifts from lower elevations to higher ones in the first half of a year (in the Northern Hemisphere). Typically, maximum seasonal snowmelt occurs 2-3 months prior to that of glacier runoff (Zhetker and Tsarev 1991; Kumar 2011).

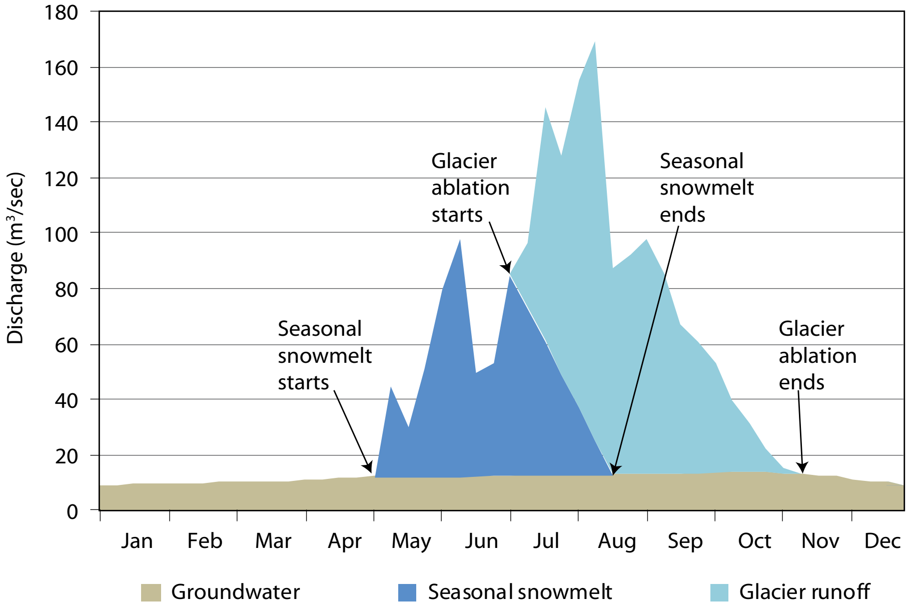
Methods of Meltwater Assessments: A Review

Estimating basin-scale glacier runoff remains a challenge in many alpine regions (Viviroli et al. 2011; Bolch et al. 2012). The direct measurements of flow in streams originating from glaciers (pro-glacial streams) are extremely rare, because of technical difficulties and other factors. For instance, glacier discharge is not necessarily channelled to a single stream, whereas seasonal snowmelt from ice-free rock slopes in the immediate glacier surroundings is in most instances routed to pro-glacial streams, which makes gauging pro-glacial streams an inaccurate method of evaluating glacier runoff even in case studies. The isotope technique of differentiation between snow and ice-melt components of flow was shown to be effective in case studies, but is not applicable to a large number of glaciers (Singh and Singh 2001). Therefore, glacier runoff evaluation mainly relies on modeling approaches, particularly in large basins. The larger the basin, the more challenging it is to model the glacial runoff, because the diversity of glaciers and variability of micro-climatic conditions increases with increase in the catchment size (Hock et al. 2005; Savoskul and Smakhtin 2013).

The approaches used for spatial representation of glacier systems in hydrological models are few. In semi-distributed models, glacier systems are represented by glacier area-altitude distribution histograms of subbasins, typically with a step of 100 m (Dyurgerov et al. 1995; Tangborn and Rana 2000; Alford et al. 2009; Hagg et al. 2011; Bocchiola et al. 2011). An alternative approach is to represent a glacier (sub-) system by its overall area and mean ELA (Aizen and Loktionova 1996; Aizen and Aizen 1996, 1998; Konovalov 1997; Lebedeva 1997; Shetinnikov 1998; Xie et al. 2006; Kang et al. 2009). Fully distributed models (Irvine-Fynn et al. 2012; Boscarello et al. 2012) are rare, since up-scaling glacier areal parameters is a challenging task for basins with a large number of glaciers, most of which are of sub-grid size. Rees and Collins (2004) introduced a hypothetical 'generic glacier', a single large glacier the area of which is obtained by summing up areas of all glaciers in a grid cell. Rees and Collins (2004, 2006) used this approach to represent all glaciers from 20 x 20 km^2 cells, i.e., to make glacier distributions in large river basins matching the grid of regional climatological and hydrological models. 'Generic glacier' approach is too simplistic, in the opinion of the authors, because hydrological properties of large glaciers and small glaciers may differ a lot (Singh and Singh 2001). Given the current state of knowledge and availability of data, semi-distributed modeling with subbasins being represented by the glacier area and mean ELA appears to be the most suitable approach for basin-scale glacier runoff assessment, since it offers a reasonable compromise between the conflicting needs for accuracy and simplification.

The physical concepts employed for the calculation of meltwater discharge may rely either on the use of purely hydrological tools or a range of glaciological techniques. The hydrograph separation method is the most basic. Graphical separation technique (Kemmerikh 1972), for instance, was applied in the Aral Sea region under the following assumptions: i) the baseflow is defined as the lowest cold season flow; ii) the seasonal snowmelt peak occurs before glacier ablation starts; and iii) seasonal snowmelt diminishes at a constant recession rate from its current value to zero from the beginning of glacier ablation to the date when non-glaciated terrain becomes snow-free. In environments where contribution from other sources (rain) is negligible, the hydrographs of medium-sized alpine catchments can be separated into sections representing baseflow (inflow from groundwater) and seasonal snowmelt (Figure 3), with the remaining part of a hydrograph representing glacier runoff. Hydrograph separation offers an accuracy of ±20-30% for the assessment of glacier runoff and snowmelt, which can be improved through application of chemical and isotopic approaches (Brown and Tranter 1990; Kong and Pang 2012), but is hardly applicable to basin-scale studies since it requires a lot of sampling.

FIGURE 3. The diagram explaining hydrograph separation in the Aral Sea region, where rainwater contribution to river flow is negligible. Data used in this diagram show hydrograph of Sokh, left tributary of Syr Darya River at Sarykandy gauge in 1961 (a year of normal flow). Glaciated area of the catchment is 170 km^2.



Data source: Kemmerikh 1972.

Another group of methods for melt flow estimation is the so-called temperature-index methods, where air temperature is an input variable. The most popular among this group is the degree-day method, based on the assumption that the specific value of daily melt (MW, mm/day) is a linear function of daily air temperature (T, °C) on days when T > 0 °C:

$$MW = DDF * T \quad (5)$$

where: DDF (mm/°C day) is an empirical degree-day factor (Braithwaite 1985; Hock 2003; Hock et al. 2005; Braithwaite et al. 2006). In a typical application of this method, total glacier or snowmelt runoff from a catchment is calculated as an integration of subtotals from a range of elevation belts based on glacier or snow area within each elevation belt (Hagg and Braun 2006; Hagg et al. 2007, 2011). The degree-day method is also broadly used for the assessment of discharge from glaciated catchments without subdividing it into components (Archer and Fowler 2004; Konz et al. 2007; Arora et al. 2008; Braun et al. 2009; Rupper and Roe 2008).

Another temperature-index method (Krenke 1982) is based on the assumption that specific annual ablation (A, mm) irrespective of the duration of the ablation period, is a power function of mean summer (June-August) temperature (T_S, °C) at ELA:

$$A = k * (T_S + I)^n \quad (6)$$

where: k, I and n are empirical coefficients. The method was developed originally for the Western Tien Shan and applied in Pamir (Ananicheva and Davidovich 1997) and Northern Tien Shan (Vilesov 1999).

Among the methods relying on glacier mass budget, the one based on glacier regime evaluation is the most common (Glazirin 1985; Dyurgerov et al. 1995; Aizen and Aizen 1996; Aizen et al. 2002; Alford et al. 2009; Alford and Armstrong 2010). The method is typically applied under an assumption that steady-state specific values of glacier mass budget items at ELA represent their glacier-average specific values.

This means that specific glacier runoff equals glacier runoff depth at ELA. Since glacier regime is strongly controlled by regional climate and has a relatively low local variability of ±30% (Krenke 1982; Glazirin 1985), the total glacier runoff (GR) from a glaciated catchment can be calculated based on specific glacier runoff at ELA (GR_{ELA}) and total glacier-covered area (A_G) as:

$$GR = GR_{ELA} * A_G \quad (7)$$

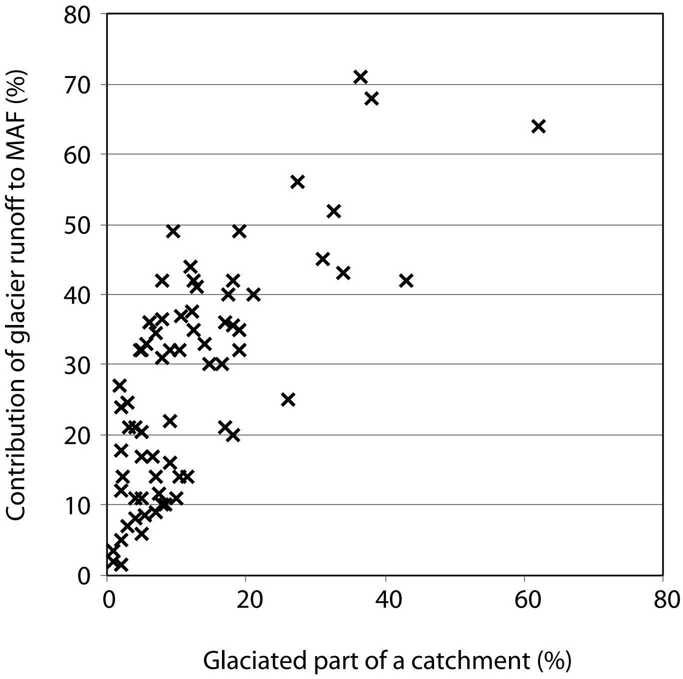
The largest problem that any large-scale glacio-hydrological study faces is the scarcity of data for model calibration (Bolch et al. 2012; Pellicciotti et al. 2012; Konz and Devkota 2009). Direct measurements of accumulation and ablation – an integral part of any in-situ glacier mass balance monitoring (Kaser et al. 2003) – could be ideal for the verification of glacier runoff models. Yet, such data are only occasionally reported in research papers and reviews (Aizen and Aizen 1994; Hewitt et al. 1989; Fujita et al. 1998, 2001a, 2001b; Dyurgerov et al. 1995; Bhutiyani 1999; Sharma 1999; Aizen et al. 2002; Mayer et al. 2006; Wagnon et al. 2007; Dobhal et al. 2008; Yang et al. 2008; Dyurgerov 2010; Pithan 2011), but do not appear in the publications of the World Glacier Monitoring Service (WGMS 1991, 1993, 1994, 1996, 1999; 2001, 2003, 2005, 2007, 2009, 2011), which report only the net values of glacier mass balance and not the measured mass-balance items, i.e., ablation and accumulation. Direct measurements of ice flow velocity and glacier thickness at ELA, which can be used as proxy of glacier regime, are also rare (Mayer et al. 2006).

Due to the scarcity of direct measurements of glacier runoff and glacier mass budget items, glacier runoff estimation becomes strongly dependent on climatological information as the second principal tool of model calibration. However, these data are equally inadequate. Currently available meteorological records for high mountains are few and do not capture high spatial and temporal heterogeneity of the alpine climate (Archer 2003; Fowler and Archer 2006; Bhutiyani et al. 2007; Forsythe et al. 2010; Mukhopadhyay and Dutta 2010). Out of 962 meteorological stations in the Hindu Kush-Himalayan (HKH) region only 38 are located above 4,000 m, and only 64 are at elevations between 3,000 and 4,000 m. The attempts to improve the network of conventional meteorological stations by installation of automated ones at high elevations in the past few decades have hardly been sufficient (Winiger et al. 2005; Eriksson et al. 2009; Schiermeier 2010; Bradley 2011).

Synthetic climatological datasets too are insufficiently accurate, particularly for precipitation, since they at best reflect orographic and rain shadow effects, but are not suitable for reproducing effects of wind and snow avalanches, which play an important role in the alpine settings as agents of snow relocation (Young and Hewitt 1990; Zhetker and Tsarev 1991). Because of the rugged alpine topography, any concave shape of meso-relief in the mountains makes a trap for preferential snow accumulation, in many locations sufficient for sustaining a glacier. The relocation of snow in some settings may result in much higher snow concentration, up to 300-400% compared to what might be expected from regional precipitation norm, but not necessarily (Krenke 1982; Glazirin 1985). Because of that, specific glacier runoff in some catchments may be much higher than runoff depth from ice-free areas. However, in other cases, the difference between the former and the latter may be negligible, as illustrated in Figure 4. Therefore, the region-average and elevation-average precipitation estimates based on re-analysis of datasets and regional climate models too, are likely to lead to inaccurate estimates of precipitation received by glaciers and, hence, to unreliable glacier runoff assessments.

Spatial variability of annual precipitation in the upper parts of the study basins is in the range of 300-3,000 mm in the HKH region, and 250-2,500 mm in the Aral Sea region (Zhetker and Tsarev 1991; Kotlyakov 1997; Winiger et al. 2005; Kotlyakov and Lebedeva 1999). Since the magnitude of its variability within short distances is extremely high, a reliable assessment of the amount of precipitation received by glaciers is a particularly challenging task (Young and Hewitt 1990, 1993; Winiger et al. 2005; Fowler and Archer 2005, 2006; Forsythe et al. 2010; Hewitt 2005; Immerzeel et al. 2012). In comparison to precipitation, air temperature at ELA varies in

FIGURE 4. Preferential accumulation of snow over glaciated areas makes glaciers major contributors to MAF in small- to medium-sized catchments in the Amu Darya Basin. High scatter of the points implies that the variability of snow concentration is extremely large and, therefore, difficult to model in basin-scale studies.



Data source: Shetinnikov 1998.

a more predictable manner, mainly depending on the elevation and macro-topography, in a range of approximately 10 °C, from +5 °C to –5 °C (June-August). To infer the air temperature at the elevations of glacier occurrence from meteorological records, lapse rates approaches are used, e.g., adiabatic gradient and rock – ice surface transition gradient (Mihalcea et al. 2006; Forsythe et al. 2010; Mukhopadhyay and Dutta 2010; Braithwaite et al. 2006; Kang et al. 2009), which are the major sources of considerable inaccuracy in the air temperature estimates obtained by interpolation of the data from the nearest meteorological station.

In the authors' view, under the current state of knowledge, practically everywhere in High Asia, for the elevations of glacier occurrence, i.e., above 3,000 m, the accuracy of air temperature estimates is in the order of ±2 °C. For precipitation, the accuracy is ±500 mm/year for humid areas and ±150 mm/year for the arid areas, i.e., around ±30% at best. This accuracy assessment is based on expert estimates and consideration of typical adiabatic lapse rates (0.55-0.75 °C/100 m) used to infer air temperature at ELA from the nearest meteorological stations and typical elevation difference between the stations and ELA (around 2,000 m).

In light of the high uncertainties in climatological data, suitability of methods used for the assessment of glacier runoff and snowmelt for the basin-scale studies can be critically re-evaluated as follows. Temperature-index methods are, by definition, highly sensitive to the inaccuracies in air temperature estimates. An inaccuracy in the order of ±2 °C in estimating daily or average summer air temperature (which is, on average, between +10 °C and 0 °C at ELA in the summer time) alone may result in inaccuracies of up to ±50% for the temperature index-based runoff estimates (Equations 5 and 6). Another major source of uncertainty is associated with the DDF value (Equation 5). In large-scale studies, a DDF value of 6-10 mm/°C day is typically adopted, which increases the method's uncertainly to over ±100%, since field measurements suggest that actual DDF can vary from 1 to 16 mm/°C day (Singh and Kumar 1996; Singh et al. 1997, 2008; Dyurgerov et al. 1995; Kayastha et al. 2000a, 2003, 2005; Zhang et al. 2006). In the highly heterogeneous alpine environments, DDF is greatly affected by local factors such as density, water saturation and dust/debris content of snow and ice (Martinec 1989; Braithwaite et al. 2006; Mukhopadhyay and Dutta 2010; Hagg et al. 2011), but current understanding of spatial and temporal variability of DDF remains limited, despite much theorization (Singh and Kumar 1996; Kayastha et al. 2003; Hock 2003; Zhang et al. 2006; Aizen et al. 2006). For instance, thin layers of dust, sand and loose debris facilitate melting, but a noticeable decrease of surface ablation rate is observed under a debris layer of 2-3 cm thickness, and melting is almost entirely blocked under debris over 1 m in thickness (Tangborn and Rana 2000; Konovalov 2000; Pelto 2000; Mattson 2000; Kayastha et al. 2000b; Singh and Singh 2001; Hagg et al. 2008). Since no measurements of debris thickness with an accuracy of ±0.2-0.3 m are available for large territories, whereas on individual glaciers it changes randomly from 0 m to over 1.5 m (Savoskul, O., field observations from over 100 glaciers in Tien Shan), any assumption of melting rates under a debris layer potentially increases inaccuracy of the runoff assessment too. Besides, temperature-index methods are not suited for assessment of intra- and sub-glacial melting. The latter adds up to 5-15% to flow annually (Dyurgerov et al. 1995; Mukhopadhyay and Dutta 2010; Singh and Singh 2001). Adding the components that describe net radiation (e.g., Kustas et al. 1994) into models, or introducing different values of DDF for glaciers of different orientation (Brubaker et al. 1996; Hagg et al. 2011), may improve the method's performance, but the remaining uncertainties are still in order of ±50-100% at best.

The uncertainty associated with glacier regime-based methods is determined primarily by the accuracy of the mass-budget evaluations, which have an accuracy of ±30%, related to inaccuracies of precipitation assessments. The latter figure thus determines the overall uncertainty of glacier mass budget methods. The uncertainty may be effectively minimized, since application of glacier mass budget approach allows cross-validation of the mass budget principal items, i.e., accumulation and ablation (Aizen and Loktionova 1996; Aizen et al. 2002; Braithwaite et al. 2006; Thayyen et al. 2007; Hagg et al. 2011). The advantage of glacier regime-based approach is that once GR_{ELA} is established, the runoff model (Equation 7) becomes independent of the topographic control and needs only A_G as an input parameter. Because of relatively low local variability of accumulation and ablation net values at ELA, even a few case studies within more or less homogenous territories are sufficient for the calibration of this model (Krenke 1982; Glazirin 1985). Another advantage of glacier regime-based approach is that it allows renewable and nonrenewable components of glacier runoff to be calculated separately, contrary to temperature-index and hydrograph separation methods. Thus, because of high inaccuracy (up to ±50-100%) of temperature-index methods for glacier runoff assessment in basin-scale applications, these methods cannot be recommended for glacier runoff estimations in basin-scale studies. Application of glacier mass budget and hydrograph separation methods for this purpose offers the best currently possible accuracy within a ±30% range, with both methods performing well in semi-distributed models.

As for simulating snowmelt contribution to MAF, temperature-index methods offer an ideal solution. The snowmelt assessment faces challenges similar to glacier runoff assessment. In particular, shortage of climatological information for the alpine regions makes modeling the only way of evaluating snowmelt (Barnett et al. 2005; Rees and Collins 2006; Immerzeel et al. 2009, 2010). However, in the case of snowmelt, model calibration is easier (Singh and Singh 2001). Because of the significantly larger areal extent of seasonal snow cover, compared to glaciers, snowmelt simulations can be driven by remotely sensed data of snow cover extent and its inter-annual changes with high degree of temporal and spatial resolution (Willmott et al. 1985; Zhetker and Tsarev 1991; Qobilov et al. 2000; Willmott and Matsuura 2006; Gurung et al. 2011; Butt 2012; Majeed et al. 2009). The gauged flow is better suited for snowmelt models' calibration too, because the snowmelt is the principal contributor to the flow till the peak of the melting season (Singh and Jain 2003; Kumar 2011). Physical concepts used in snowmelt modeling in alpine regions are more simple, and in practical applications, limited to temperature index-based approach (Singh et al. 1995; Hock 2003). The best results are obtained by combining the methods, which allows cross-validation of the water budget of the snow cover, i.e., evaluation of the net melt value by the assessment of the net snow accumulation (Aizen et al. 1995, 1997; Singh and Jain 2003; Singh and Bengtsson 2004; Willmott and Matsuura 2006; Immerzeel et al. 2010). Spatial representation of snow cover areal distribution may be fully distributed using grids of various spatial resolutions or may rely on an elevation belt approach in semi-distributed models. The major challenge in assessing contribution from snowmelt to streamflow is related to the fact that snowmelt occurs over large areas and, contrary to glacier runoff, is not instantly channelled to streamflow. Under-accounting of the losses to groundwater aquifers from surface snowmelt may lead to over-estimation of its contribution to MAF.

Current State of Knowledge on Glacier Runoff in the Study Basins

To the best of the authors' knowledge, no comprehensive basin-wide assessments of glacier runoff have been carried out for the HKH region. As Armstrong (2010, 11-12) observes, "we have no direct quantitative measurement of how much glacier meltwater is being contributed to the river system leaving the basin containing glaciers… In summary, a highly accurate assessment of the significance of snow and glacier melt in the overall Asian river hydrology remains largely unaccomplished." The message is echoed by Viviroli et al. (2011, 476), "It is also difficult to make a clear quantitative distinction between the contribution from melting of inter-annual snowpack and from glaciers." Lamadrid and MacClune (2010, 22) list 29 large-scale hydrological models available for High Asia with the main conclusion that, "a large-scale study is feasible in terms of institutional, technical and scientific capacity," observing at the same time that, "efforts to date have been piecemeal."

This is somewhat surprising, given the fact there is a wealth of publications on 'glacier-melt' in the HKH region, and yet virtually no credible basin-scale assessments had ever been published. Few of the review reports randomly cite estimates of flow from glaciated catchments and estimates of snowmelt as 'glacier-melt' without going into nuances of terminology and methodology (Xu et al. 2007; Eriksson et al. 2009; Hasnain 2009; Cruz et al. 2007; Raina 2009). For instance, Xu et al. (2007) and Eriksson et al. (2009) estimate glacier contribution to MAF as 44.8% for the Indus, 9.1% for the Ganges, 12.3% for the Brahmaputra and 6.6% for the Mekong basins without any explanation of the methodology used. Barnett et al. (2005, 306) states, "HKH region: ... there is little doubt that melting glaciers provide a key source of water for the region in the summer months: as much as 70% of the summer flow in the Ganges and 50-60% of the flow in other major rivers", which also does not get any justification. Mass media and other grey sources pick up some of those figures and trumpet high alarms: "The melting of glaciers seasonally releases meltwater into tributaries of the Indus, Ganges and Brahmaputra rivers, with glacial melt contributing up to 45% of the total river flow." (Hasnain 2009). "The Indus… highlighted as one of the world's 10 big at-risk rivers because retreating glaciers provide 70-80% of its flow"

(Jowit 2008). Yet, no evidence is provided to support any of those assessments either.

Such contradictions are partially due to the fact that compilation of the results of dozens of miscellaneous studies is a challenging task, which is hampered further by the absence of a common understanding of the terms and by the lack of reporting standards for describing glacier runoff. The latter may be presented as daily discharge for an unknown time interval (most likely a daily discharge in the peak season, which gives no idea of the annual total discharge) (Raina 2009), or an average glacier runoff contribution to MAF of several drainage systems (Yao et al. 2007).

To make published data compatible, the cited figures in this report have been converted into annual specific glacier runoff (mm w.e., hereafter mm), wherever it was possible.

Another problem associated with use of published sources is simply the scarcity of glacier runoff estimates in peer-reviewed papers. An analysis of publications on modeling runoff from large- and medium-scale glaciated catchments (Lebedeva 1997; Singh et al. 1997, 2008; Singh and Jain 2002; Aizen and Aizen 1998; Rees and Collins 2004; Hagg and Braun 2006; Konz et al. 2007; Yao et al. 2007; Hagg et al. 2008, 2011; Immerzeel et al. 2009, 2010; Majeed et al. 2009; Bookhagen and Burbank 2010; Gosain et al. 2010; Kumar et al. 2010; Mukhopadhyay and Dutta 2010) indicates that not many of these dealt with modeling glacier runoff per se. Even fewer report their evaluations of glacier runoff separately from snowmelt, if at all. The latter too are hardly compatible with each other due to methodological differences.

For example, Immerzeel et al. (2010) evaluate the importance of meltwater from the upstream areas in the Indus, the Brahmaputra and the Ganges basins on overall basin hydrology, using normalized melt index (NMI), which is defined as "the volumetric snow and glacier upstream discharge divided by the downstream natural discharge. Upstream discharge is calculated with a calibrated snowmelt runoff model. Downstream natural discharge is calculated by subtracting the natural evaporation of the basins, calculated with a hydrological model, from precipitation" (p. 1383). The authors argue that NMI is "a more reliable measure than the commonly used meltwater fractions of total river discharge" (p. 1383). While this may be true, the use of NMI makes their results non-compatible with other studies in the region. To estimate the specific glacier runoff for each basin from the data given by Immerzeel et al. (2010), the annual meltwater volume has to be (i) deduced from the hydrograph of the simulated upstream flow, (ii) subdivided into seasonal snowmelt from ice-free areas and glacier runoff according to the ratio given in that paper (Immerzeel et al. 2010), and (iii) normalized by the glaciated area of each basin. The figures obtained after this operation are approximately 2,300 mm/year, 1,500 mm/year and 2,200 mm/year in the Indus, Ganges and Brahmaputra basins, respectively. The total mean annual glacier runoff from these three basins based on these data is 49 km^3, 13 km^3 and 31 km^3, respectively.

Lebedeva (1997) used glacier mass budget accounting to estimate mean glacier runoff from two major Afghanistan sub-catchments (Kunar and Panjshir rivers) of the Indus Basin. Glacier runoff was found to contribute 3 km^3 (18%) to MAF of both rivers, which corresponds to specific glacier runoff from those sub-catchments of 1,760 mm/year in Kunar and 2,015 mm/year in Panjshir.

In the study by Asia-Pacific Network for Global Change Research (APN 2005), the results of temperature index-based simulation of glacier runoff from the Upper Indus Basin are given as a hydrograph only. Simulated total glacier runoff derived from that hydrograph is approximately 3 km^3 and 33 km^3 for the Hunza catchment and Upper Indus Basin, respectively. If the latter estimates were accurate, it would imply that glaciers contribute 42% to the Upper Indus flow at the Besham Qila gauging station. This figure is likely, however, to be an over-estimation, since the major part of the Upper Indus Basin has similar climatic conditions to the Hunza subbasin and thus could be expected to have approximately the same specific glacier runoff. Yet, the analysis of the hydrograph given in APN (2005) suggests that specific mean glacier runoff from the rain-shadowed Hunza catchment nested in the Upper Indus Basin is roughly 700 mm/year, whereas the entire Upper Indus Basin produces approximately 2,150 mm/year from glaciated areas.

Bocchiola et al. (2011) evaluate only the ice-melt component of glacier runoff. The study area is the catchment of Shigar River, another tributary of the Upper Indus, with an estimated glaciated area of 2,774 km^2 (534 km^2 higher than reported by Mool et al. 2005). The ice-melt evaluation of Bocchiola et al. (2011) based on the temperature-index approach is 870 mm/year, i.e., equal to 2.41 km^3 in terms of contribution to the basin's flow.

Field measurement from the first, second and fourth largest glaciers in the Indus Basin suggest that specific glacier runoff from their surface varies between 600 mm/year and 1,400 mm/year (Hewitt et al. 1989; Bhutiyani 1999; Mayer et al. 2006; Mihalcea et al. 2006). However, it is not clear how representative these results are for the entire basin, since the sample is small and is represented only by the largest glaciers.

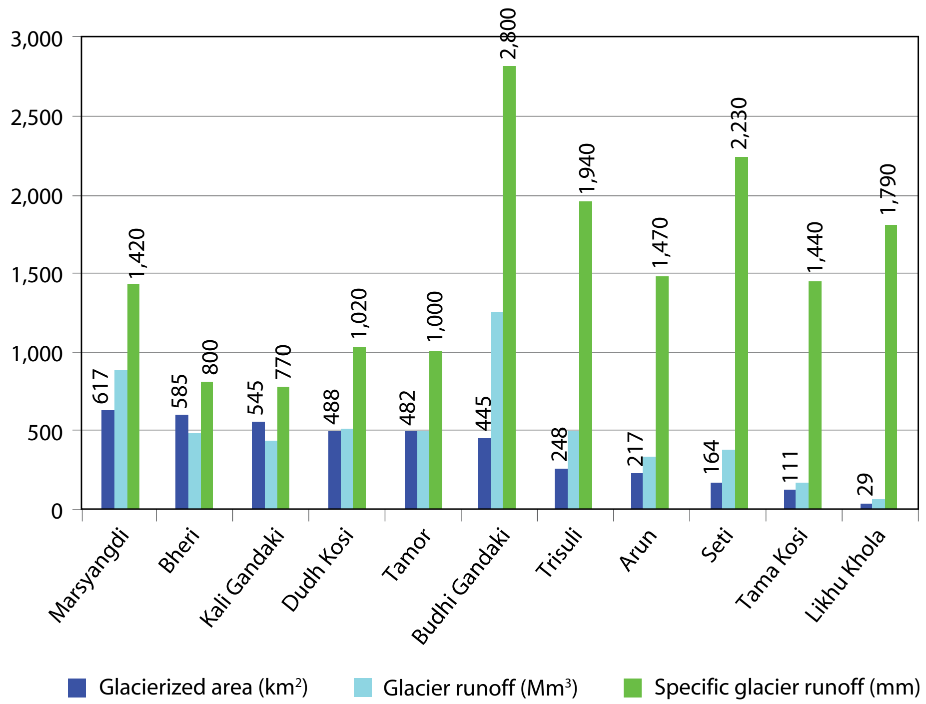
Alford et al. (2009) (summed up in Alford and Armstrong 2010) examine glaciers and glacier discharge in Nepal zooming on nine sub-catchments of Ganges left tributaries with a total glaciated area of 3,644 km^2 and conclude that glaciers contribute 2-3% to the discharge of all rivers, flowing from Nepal, i.e., 5.38 km^3 in total, which indicates that specific glacier runoff from this area is about 1,500 mm/year. In another research, conducted recently in Nepal Himalaya, the summary of glacier and seasonal snow contribution to MAF is estimated as 14 km^3, i.e., about 10% of MAF from Nepal (Andermann et al. 2012). However, since snowmelt in the latter publication is not assessed separately from glacier runoff, the results of Andermann et al. (2012) are not compatible with the data of Alford et al. (2009) and Alford and Armstrong (2010).

So far, the results of Alford et al. (2009) illustrated in Figure 5 represent the most detailed large-scale study to date carried out in the HKH region. Yet, they are not sufficient for the assessment of the net glacier runoff from the entire Ganges Basin. The accuracy of the assessment of Alford et al. (2009) might suffer somewhat from the assumption that "all melt occurs below ELA" (Alford et al. 2009, 18), which is likely to result in underestimation of the actual values by under-accounting of the melt occurring above ELA, and this may be significant (e.g., Mayer et al. 2006; Figure 2). Other sources of uncertainty in Alford et al. (2009) may include: i) limited field verification of actual ablation rates in the region; ii) use of hypothetical ELA values, although the data assimilated for the study allow more accurate estimates of mean ELA for each sub-catchment; and iii) under-accounting of glacier runoff from the altitudinal belts outside the interval from 4,000 m to 6,000 m. Besides, the findings of Alford et al. (2009) imply that specific glacier runoff is less than specific runoff from non-glaciated terrain, which would be possible only if snow were concentrated on ice-free terrain instead of glaciers, i.e., requires assumptions contradictory to basic glaciological knowledge. Besides, a detailed field study in the Gangotri sub-catchment indicates that, "a major contribution in the study basin comes from melting in the glaciated part of the basin" (Singh et al. 2008).

Specific glacier runoff at the rain-shadowed northern macro-slope of Central Himalaya near Xixibangma Peak is evaluated by Aizen et al. (2002) as 600 mm/year, which is supposed to yield 0.14 km^3 of glacier runoff annually from 230 km^2 of ice-covered area. Although the flow from this area is contributing to the Ganges Basin, specific glacier runoff can be considered representative for the uppermost part of the Brahmaputra Basin too, for which (Brahmaputra Basin) there are virtually no data, apart from regional estimates presented in Kotlyakov (1997) and Immerzeel et al. (2010).

Atlas of Snow and Glacier Resources of the World (Kotlyakov 1997), published in Russian and, therefore, mostly unknown to the international research community, represents a unique attempt to synthesize all available climatological data and basic glaciological knowledge. This publication contains i.a. the maps of glacier regime in the HKH region, showing spatial variability of specific values of glacier accumulation and ablation at ELA with detailed spatial resolution. This product represents the most methodologically coherent and physically plausible source of data on specific rates of glacier ablation covering all study basins in the HKH region.

FIGURE 5. Glaciated area and glacier runoff in major sub-catchments of Nepal Himalaya.



Data source: Alford et al. 2009.

Case studies from single glaciers in the HKH region, although few in number (Fujita and Nakawo 1997; Fujita et al. 1998, 2001a; Bhutiyani 1999; Mihalcea et al. 2006; Mayer et al. 2006; Kumar et al. 2002; Tangborn and Rana 2000; Swaroop et al. 2001; Hasnain and Thayyen 1999; Thayyen et al. 2007; Thayyen and Gerdan 2010), are suitable for calculations of specific glacier runoff rates.

The data assembled in Table 2 are certainly rather sporadic, but after exclusion of apparent errors (shown in curly brackets), they appear to support a geographically plausible spatial variability of specific glacier runoff in the region, established by Kotlyakov (1997) and suggested by the results of other large-scale assessments in the region (Dyurgerov et al. 1995; Lebedeva 1997; Shetinnikov 1998; Alford et al. 2009; Alford and Armstrong 2010). Analysis of available data on specific glacier runoff in the HKH region suggests that, depending on their location within the catchment, glaciers in the Indus Basin discharge, on average, between 500 and 2,500 mm/year from their surface to MAF, and in the Ganges Basin – 800 to 3,000 mm/year. In the Brahmaputra Basin, the specific glacier runoff is around 500-750 mm/year in the western upper part, 750-1,000 mm/year in the eastern upper catchment and 1,500-2,500 mm/year from southern Himalaya macro-slope.

The Aral Sea region is studied significantly better compared to the HKH region. For the Amu Darya and Syr Darya basins, a number of large-scale glacier runoff assessments have been carried out starting from 1938 (L'vovich 1938; Shults 1965; Sheglova 1960; Kemmerikh 1972; Kamalov 1974; Krenke 1980, 1982; Konovalov 1985; Ratsek 1991; Sokalskaya 1994; Dyurgerov et al. 1995; Lebedeva 1997; Shetinnikov 1976, 1998; Mamatkanov et al. 2006; Kuzmichenok 2009). However, since all the works published before the 2000s appeared in Russian, they remain largely unknown to the international audience. A rare exception is a recent assessment of glacier runoff in the Tien Shan Mountains, which is based on the overview of several sources published in Russian (Sorg at al. 2012).

TABLE 2. Authors' estimates of specific glacier runoff in the study basins based on published sources.

Location	Glaciated area (km^2)	Specific glacier runoff (mm/year)	Method	Source, comments
		INDUS BASIN		
Upper Basin till Besham Qila gauge	15,061	2,150	MB, TI	APN 2005, likely to be an over-estimate
Upper Basin till Besham Qila gauge	15,061	1,500 total, of this 666 nonrenewable	TI	Immerzeel et al. 2009
Hunza catchment	4,677	700	MB, TI	APN 2005
Kunar catchment	1,621	1,760	MB	Lebedeva 1997
Panjshir	67	2,015	MB	
Siachen glacier system	1,056	1,390	MB	Bhutiyani 1999
Baltoro glacier	641	550	IFV	Mayer et al. 2006; Michalcea et al. 2006
Biafo glacier system	628	1,114	IFV, MB	Hewitt et al. 1989
Karakoram	n.a.	750-2,000	MB	Kotlyakov 1997
Tibet (Chinese part of the basin)	n.a.	500-750	MB	Kotlyakov 1997
West Himalaya	n.a.	1,000-2,500	MB	Kotlyakov 1997
Entire Indus Basin	21,000	2,300	TI	Immerzeel et al. 2010
	20,325	{300}	MB, TI	Kaser et al. 2010, underestimate
	25,000	{3,700}	C	Barnett et al. 2005, unrealistic over-estimate
	n.s.	{4,600}	C	Eriksson et al. 2009; Xu et al. 2007, unrealistic over-estimate
	n.s.	{6,500-7,400}	n.s.	Jowit 2008, unrealistic over-estimate
		GANGES BASIN		
Nepal, nine major catchments	3,644	800-2,800	MB	Alford et al. 2009
Nepal, Marsyangdi catchment	432	2,600	MB	Alford and Armstrong 2010
Langtang catchment	n.s.	700-1,500	TI	Kayastha et al. 2005
Lirung catchment	n.s.	1,200-2,200	TI	Kayastha et al. 2005
North Himalaya, Xixibangma Mountain	230	600	MB	Aizen et al. 2002
Central Himalaya, south marco-slope	n.a.	1,000-2,500	MB	Kotlyakov and Lebedeva 1999
Gangotri catchment	500	1,900-2,000	MB, TI	Kumar et al. 2002
Entire Ganges Basin	9,000	1,500	TI	Immerzeel et al. 2010
	n.s.	2,600	n.s. C	Eriksson et al. 2009; Xu et al. 2007
	12,659	{370}	MB, TI	Kaser et al. 2010, underestimate

(Continued)

TABLE 2. Authors' estimates of specific glacier runoff in the study basins based on published sources (Continued).

Location	Glaciated area (km^2)	Specific glacier runoff (mm/year)	Method	Source, comments
		BRAHMAPUTRA BASIN		
Central and East Himalaya	n.a.	1,500-2,500	MB	Kotlyakov 1997
Tibet SE	n.a.	500-1,000	MB	Kotlyakov 1997
Tibet SW	n.a.	<500	MB	Kotlyakov 1997
Upper Basin	n.a.	600-1,600	n.a.	Xie et al. 2006
Tibet, South	n.a.	{2,000}	TI	Kang et al. 2009, over-estimate due to use of non-calibrated models
Entire Brahmaputra Basin	14,000	2,200	TI	Immerzeel et al. 2010
	n.a.	{4,900}	n.s. C	Eriksson et al. 2009; Xu et al. 2007, extreme over-estimate
	16,118	{410}	MB, TI	Kaser et al. 2010, underestimate
		AMU DARYA BASIN		
Zerafsan	557	2,730	HS	Kemmerikh 1972
Kafiringan, Surkhandarya, Kashkadarya	250	2,680		
Vakhsh	4,117	1,220		
Pyanj (within former USSR)	3,520	1,300		
Ghunt	735	1,180		
Yazgulem	306	1,430		
Vanch	380	1,610		
Obihingou	750	2,030		
Amu Darya (Hissar-Alay)	670	480 580	MB MB	Kuzmichenok 2009 Mamatkanov et al. 2006
Amu Darya (Pamir in Tajikistan)	5,808	1,020	MB	Shetinnikov 1998
Amu Darya (Hissar-Alay in Tajikistan)	1,689	1,690	MB	Shetinnikov 1998
Amu Darya left tributaries (Afghanistan)	3,118	2,350	MB	Lebedeva 1997
Amu Darya (within former USSR, i.e., Pamir and Gissar-Alay)	8,454	1,390	HS	Kemmerikh 1972 Glacier status of ca. 1960
Amu Darya (within former USSR, i.e., Pamir and Gissar-Alay)	7,497	1,170	MB	Shetinnikov 1998 Glacier status of 1980

(Continued)

TABLE 2. Authors' estimates of specific glacier runoff in the study basins based on published sources (Continued).

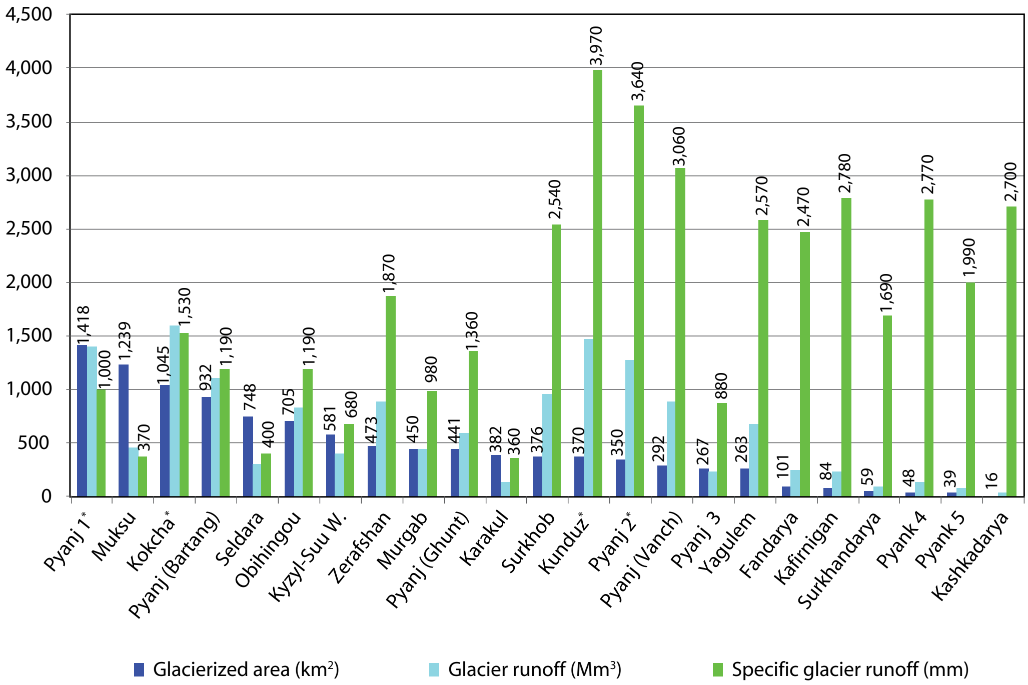
Location	Glaciated area (km^2)	Specific glacier runoff (mm/year)	Method	Source, comments
SYR DARYA BASIN				
Pskem	128	1,470	MB	Konovalov 1985
		1,530	MB	Krenke 1980
		2,200	HS	Kemmerikh 1972
Chirchik	179	1,590	MB	Shetinnikov 1976
Chatkal	51	1,490	MB	Krenke 1980
Chirchik, Arys, Angren	215	2,790	HS	Kemmerikh 1972
Bolshoy Naryn	619	580	MB	Ratsek 1991
		760	n.s.	Kamalov 1974
Maliy Naryn	356	710	MB, HS	Ratsek 1991
Naryn	1,370	660	MB	Krenke 1980
		850	MB	Dyurgerov et al. 1995
		930	HS	Scheglova 1960
		950	HS	Kemmerikh 1972
		660-830	n.s.	Kamalov 1974
Fergana	917	1,580	HS	Kemmerikh 1972
Syr Darya (Tien Shan)	1,658	970	MB	Dyurgerov et al. 1995
Syr Darya (Hissar-Alay)	591	1,280	MB	Shetinnikov 1998
Syr Darya Basin	2,000	820-900	C	Sorg et al. 2012, likely to be an underestimation
Syr Darya Basin	2,522	1,250	C	This study, glacier status ca. 1960
Aral Sea Region	n.a.	650	MB, TI	Kaser et al. 2010, likely to be an underestimation
MEKONG BASIN				
Mekong Basin	n.a.	{63,000}	C	Eriksson et al. 2009; Xu et al. 2007, unrealistic over-estimate

Notes: Methods: C – compilation; HS – hydrograph separation; IFV – measurements of ice-flux velocity at ELA; MB – glacier mass budget estimates and modelling; TI – modelling based on temperature-index methods; n.a. – non-applicable; n.s. – not stated; figures in curly brackets are extremely unrealistic assessments.

An assessment of glacier runoff from the entire Amu Darya and Syr Darya basins can be compiled from three large-scale comprehensive assessments by Dyurgerov et al. (1995), Lebedeva (1997) and Shetinnikov (1998) (Figures 6 and 7). Shetinnikov (1998) made calculations for all glaciated right-hand tributary subbasins of Amu Darya, located in the Pamir and southern macro-slopes of the Gissar-Alay Mountains in Tajikistan. Lebedeva (1997) provided a complementing glacier runoff assessment for four major left-hand subbasins located in Afghanistan, i.e., the ‘Wakhan Corridor’ in the eastern part of Hindu Kush and the left tributaries of the Pyanj River, originating from the Badakhshan Mountains and the western part of Hindu Kush. The assessment of Shetinnikov (1998) also extends to the subbasins of the southwestern part of the Syr Darya Basin, whereas the larger complementing part of the basin, i.e., the glaciated subbasins in the Western and Inner Tien Shan, is covered by the assessment of Dyurgerov et al. (1995). The results of all three assessments are compatible, since they are based on glacier mass budgeting approach with minor modifications and reflect the glacier state during the period 1961-1990. These assessments are carried out under the assumption of steady state glaciers and hence reflect renewable component of glacier runoff only.

Glacier runoff estimates for the Amu Darya Basin by Shetinnikov (1998) and Lebedeva (1997) are presented in Figure 6. According to these sources, total glacier runoff contribution to the Amu Darya River flow makes 15.9 km^3, of which 46% originates from the left tributaries, located in Afghanistan. In the Syr Darya Basin, total glacier runoff estimate is 2.68 km^3 with 29% of it flowing from the left tributaries draining the northern macro-slope of Hissar-Alay range, as based on studies of Dyurgerov et al. (1995) and Shetinnikov (1998). Judging from these figures, on average, specific glacier runoff makes 1,560 mm/year in the Amu Darya Basin and 1,030 mm/year in the Syr Darya Basin.

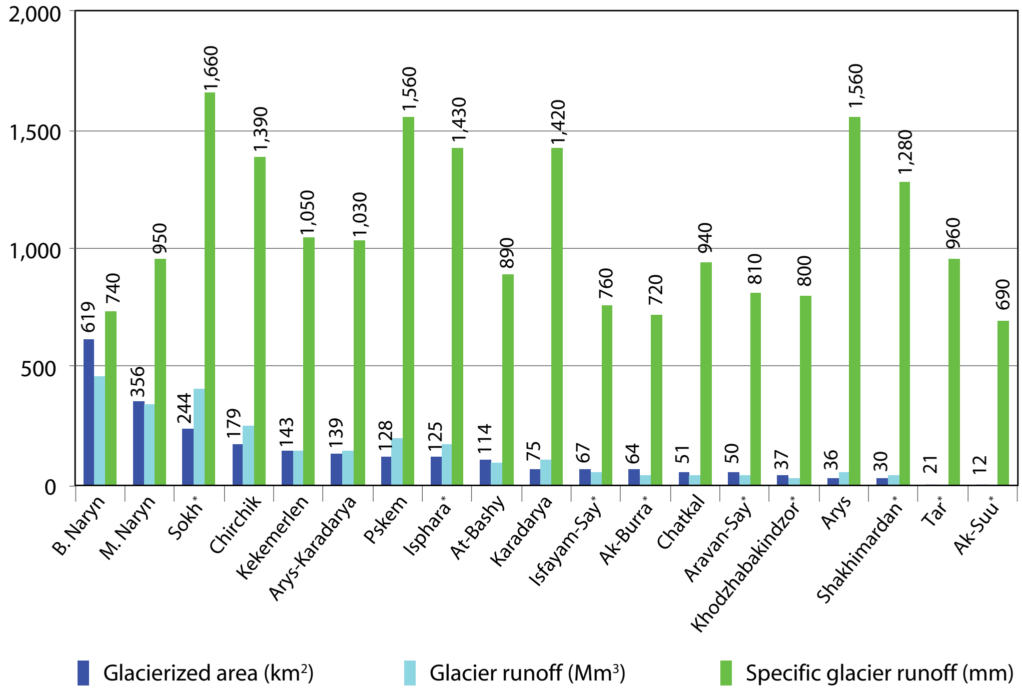
FIGURE 6. Glaciated area, total and specific glacier runoff in the major sub-catchments of Amu Darya Basin.



Data source: * Lebedeva 1997; and Shetinnikov 1998.

Notes: Pyanj 1 – upstream left tributaries (Wakhan group); Pyanj 2 – midstream left tributaries; Pyanj 3 – right tributaries upstream of Ghunt; Pyanj 4 - right tributaries between Ghunt and Yazgulem; Pyanj 5 – right tributaries between Vaksh and Vanch.

FIGURE 7. Glaciated area, total and specific glacier runoff in the major sub-catchments of the Syr Darya Basin.



Data source: Dyurgerov et al. 1995; and * Shetinnikov 1998.

The data shown in Figures 6 and 7 indicate that, at the catchment level, specific glacier runoff varies in a very wide range, i.e., between 400 mm/year and 4,000 mm/year in the Amu Darya Basin and between 700 mm/year and 1,700 mm/year in the Syr Darya Basin. Catchment-average specific glacier runoff decreases towards rivers' headwaters in rough correlation with the decrease of annual precipitation in the same direction, the latter being due to the rain shadow effect in the interior areas of the basins (i.e., the Inner Tien Shan and the Central Pamir, respectively). Notably, the total amount of glacier runoff from a catchment shows little correlation with the catchment's glaciated area, particularly so in the Amu Darya Basin with its highly heterogeneous local climate conditions.

Another important data source for the Aral Sea region is Kemmerikh (1972) who carried out hydrograph separation of 174 hydrographs for 41 rivers fed by glaciers. According to this source, total glacier runoff from the part of the Amu Darya Basin located within the former Soviet Union boundaries (total glaciated area 8,454 km^2 based on survey of 1960) makes 11.7 km^3, which corresponds to an average specific glacier runoff of 1,390 mm/year. For the Syr Darya Basin (total glaciated area in 1960s was 2,593 km^2), the respective figures are 3.34 km^3 and 1,290 mm/year.

Sorg et al. (2012) evaluated current glacier contribution to MAF in the Syr Darya Basin as 1.64-1.79 km^3, which implies that average specific glacier runoff in the basin is 820-900 mm/year. The study of Kaser et al. (2010) suggests that specific glacier runoff in the entire Aral Sea region is around 650 mm/year. Both estimates are likely to underestimate the real volume of glacier runoff, since studies based on field surveys (Table 2) produce significantly higher values.

Overall, data sources available for the Aral Sea region provide sufficient data for the evaluation of a total renewable glacier runoff for the period 1961-1990 through compilation of the key large-scale assessments (Kemmerikh 1972; Dyurgerov et al. 1995; Lebedeva 1997; Shetinnikov 1998). There is significantly less large-scale data on the total glacier runoff for the major basins in the HKH region. However, basin-scale evaluation of the total glacier runoff in that region, which would be compatible in quality to that in the Aral Sea region, can be based on the published data on glacier regime (Kotlyakov 1997) and data on glacier covered areas available from glacier inventories for that region (WGMS and NSIDC 2009; ICIMOD 2007; Cogley 2010).

A common problem for all glacier runoff assessments in the study regions is lack of distinction between renewable and nonrenewable components of glacier runoff. This gap needs to be filled. For the Aral Sea region, for example, this can be done as follows. The estimates of Kemmerikh (1972) are 20-25% higher than those given by Dyurgerov et al. (1995) and Shetinnikov (1998). The estimate of Kemmerikh (1972) is based on the measurements of actual streamflow, which means that it already includes both renewable and nonrenewable components of glacier runoff. The assessments by Dyurgerov et al. (1995) and Shetinnikov (1998) are carried out under the assumption of glacier steady state, and as such provide an assessment of renewable glacier runoff component only. A nonrenewable component, thus, can be roughly estimated as 20-25% of total glacier runoff. The estimate refers to the period 1961-1990.

Current State of Knowledge on Seasonal Snowmelt in the Study Basins

Among the publications addressing hydrological role of seasonal snow in the HKH region (Krishna 1996, 2005; Aizen et al. 1997; Singh and Jain 2003; Singh and Bengtsson 2003, 2005; Rees and Collins 2006; Gupta et al. 2005; Immerzeel et al. 2009; Kumar et al. 2010; Shekhar et al. 2010; Tahir et al. 2011; Butt 2012), the recent publications of Immerzeel et al. (2009, 2010) present the most rigorous basin-scale assessments of seasonal snowmelt. Data presented in Immerzeel et al. (2010) suggests that the total snow contribution to MAF equals 74 km^3 (32% of MAF), 20 km^3 (4% of MAF) and 94 km^3 (14% of MAF) in the Indus, Ganges and Brahmaputra basins, respectively. Seasonal snowmelt contribution to flow in the Upper Indus Basin at Besham Qila gauge is evaluated as 40% (Immerzeel et al. 2009) using the Snowmelt Runoff Model (SRM), which suggests that glacier runoff and rain contribute 32% and 28%, respectively, to the Upper Indus flow. However, since SRM does not account for the baseflow, it is likely that these figures somewhat over-estimate the contribution from meltwater sources. In another study, where baseflow is accounted for, snowmelt contribution to the Upper Indus flow at Besham Qila gauge is estimated as 13 km^3, i.e., 19% of MAF, with estimated glacier runoff contribution to MAF of 46% (APN 2005).

In the Aral Sea region, seasonal snowmelt contribution to MAF in a number of large catchments was assessed by Kemmerikh (1972) using hydrograph separation method (Table 3). This method, however, is not compatible with the snowmelt modeling carried out by Immerzeel et al. (2009, 2010) in the HKH region. Kemmerikh (1972) suggests that a significant portion of snow and glacier-melt (25-50%) does not enter the streamflow immediately (as assumed by Immerzeel et al. 2009, 2010), but passes through groundwater aquifers, which release water into streamflow at a constant rate throughout the year and constitute altogether a different source in the flow formation. It also appears that flow redistributive properties of seasonal snow and glaciers, which cause seasonal delay in releasing water to streamflow, may be either amplified or somewhat buffered by the groundwater storage.

This idea finds support in recent findings of Andermann et al. (2012, 130) who modelled water balance of the major river basins in Nepal Himalaya and estimated that "…the annual volume of water flowing through … groundwater system represents 2/3 of the annual river discharge." Bookhagen (2012, 97-98) observes that "our understanding of the timing and relative contribution of individual hydrologic components across the Himalaya is limited... Progress in determining and predicting water resources in the Himalaya has been hampered by a number of factors… Groundwater storage adds immense complexity to this picture of Himalayan hydrology…"

Evidence provided by Andermann et al. (2012) suggests that groundwater aquifers have significant transient storage capacity and function as a seasonal buffer with a time delay of about 45 days in releasing water to the streamflow within distances in the range of 0.5-5 km from the sources. Their estimate of annual aquifer storage capacity is about 180 mm per unit area. The data presented in Table 3 suggest that its value in the alpine catchments of the Aral Sea region varies in the range 70-320 mm/year, being, on average, 150-180 mm/year, i.e., in good agreement with the data of Andermann et al. (2012). As this example illustrates, the difference between results produced by models, which do not consider groundwater recharge by snowmelt water and those which do, may be significant.

TABLE 3. Estimated MAF components in selected subbasins in the Amu Darya and Syr Darya basins.

Subbasin	Catchment area (km^2)	MAF (km^3)	Contribution to MAF							
			Seasonal snow		Groundwater		Glaciers		Rain	
			(%)	(km^3)	(%)	(km^3)	(%)	(km^3)	(%)	(km^3)
AMU DARYA BASIN										
Zerafshan	10,200	4.82	36	1.73	31	1.49	32	1.54		
Varzob	1,270	1.47	58	0.85	28	0.41	10	0.15	4	0.06
Tupolang	2,200	1.57	66	1.04	24	0.38	7	0.11	3	0.05
Yagnob	1,450	1.08	58	0.62	29	0.31	13	0.14		
Vakhsh	31,200	19.10	37	7.07	37	7.07	26	4.97		
Ghunt	13,700	3.34	35	1.17	39	1.30	25	0.83		
Shakhdarya	4,620	1.17	39	0.46	41	0.48	20	0.23		
Yazgulem	1,940	1.24	29	0.36	36	0.45	35	0.43		
Vanch	1,810	1.56	26	0.41	33	0.52	40	0.62		
SUBTOTAL	68,390	35.3	39	13.7	35	12.4	26	9.0	0.3	0.11
SYR DARYA BASIN										
Naryn	10,500	2.75	32	0.88	31	0.85	32	0.88	5	0.14
Akbuura	2,430	0.68	28	0.19	57	0.39	15	0.10		
Isphairam	2,220	0.80	28	0.22	58	0.47	14	0.11		
Shakhimardan	1,300	0.33	18	0.06	65	0.22	17	0.06		
Sokh	2,480	1.32	23	0.30	42	0.55	35	0.46		
Isphara	1,560	0.48	19	0.09	44	0.21	37	0.18		
Pskem	2,830	2.64	50	1.32	36	0.95	12	0.32		
Aksu	712	0.12	40	0.05	42	0.05	18	0.02		
SUBTOTAL	24,032	9.1	34	3.1	40	3.7	23	2.1	1.5	0.14

Data source: Kemmerikh 1972.

Glacier Runoff and Seasonal Snowmelt in 1961-1990 and 2001-2010

The review of available assessments of glacier runoff and seasonal snowmelt in the study basins reveals that under current state of the art there is not enough data in published sources to make basin-scale compilation assessment of meltwater contribution to flow in the study basins. Evaluation of glacier runoff and its contribution to MAF in this study is done using semi-distributed glacier runoff model based on Equations 2-4 and 7 and described in detail in Savoskul (2003) and Savoskul et al. (2004). The renewable and nonrenewable components of the glacier runoff in the application used for this study have been simulated separately for all glaciated catchments in the study basins. Data on glacier-covered area per catchment have been derived from the dataset that was compiled from glacier inventories and expert estimates (WGMS and NSIDC 2009; ICIMOD 2007; Cogley 2010, 2011; Bajracharya and Shrestha 2011; Savoskul and Smakhtin 2013). The model has been run for two time slices: the baseline period (1961-1990) and current period (2001-2010). Table 4 shows the data used for the calibration and validation of the model: mean values of specific glacier runoff, both renewable and nonrenewable, glacier-covered area for each basin and estimates of total glacier mass loss in the past 50 years.

The estimates of glacier mass budget items under an assumption of steady-state glaciers have been taken from Kotlyakov (1997), Dyurgerov et al. (1995), Lebedeva (1997) and Shetinnikov (1998). Condensation at ELA was assumed to be negligible and the following sublimation values at ELA were adopted: 50 mm in the Ganges and Brahmaputra tributaries from southern Himalaya, 100 mm in the Amu Darya, Syr Darya and Mekong basins and midstream tributaries to the Brahmaputra, 150 mm in the Upper Indus and 200 mm in the upper flow of Brahmaputra (Kotlyakov 1997). Evaluation of the nonrenewable component of glacier runoff has been done through year-by-year simulation of changes of glacier area and mass-balance per catchment, validated using the data on glacier areal reduction rates between 1961-1990 and 2001-2010 (Table 4) and regional assessments of the mass-balance rates compiled from all available mass-balance monitoring records (Savoskul and Smakhtin 2013). The MAF values (Table 1) adopted for the calculation of meltwater component contribution to flow are represented by estimates of natural flow, i.e., a total river flow that would be expected in the absence of withdrawals and diversions. The supplementary materials are available from IWMI web page (http://waterdata.lk.iwmi.org/snCov.php). The overall accuracy of this simulation (Table 5) is in the range of ±30%.

Seasonal snowmelt contribution to basins' MAF has been evaluated for the same time slices as for glacier runoff: 1961-1990 and 2001-2010 (represented by data for 2000-2008; the database does not extend beyond 2008). The contribution of seasonal snowmelt to MAF has been calculated by subtracting the following from monthly surface snowmelt: i) water losses to groundwater aquifer recharge; and ii) the snowmelt from glacier-covered areas, i.e., snowmelt component of glacier runoff. Seasonal snowmelt in the study basins is derived from terrestrial water budget dataset of Delaware University, USA (Willmott et al. 1985; Willmott and Matsuura 2006; http://climate.geog.udel.edu/~climate/), which has a spatial resolution of 0.5 x 0.5 degrees and a temporal resolution of 1 month. Maximum snow cover per basin and average surface monthly snowmelt have been derived from a 30-year and 9-year monthly means, respectively, for the periods of 1961-1990 (Figure 8) and 2000-2008 (Savoskul and Smakhtin 2013). Water losses to groundwater recharge were assumed to make 15 mm/month from areas that became snow-free in each month - based on data given in Andermann et al. (2012). The average snowmelt component of glacier runoff was assumed to make 50% of renewable glacier runoff, based on data of Krenke (1982), Glazirin (1985), Dyurgerov et al. (1995) and Kotlyakov (1997).

TABLE 4. Data used for the calibration and validation of glacier-runoff model.

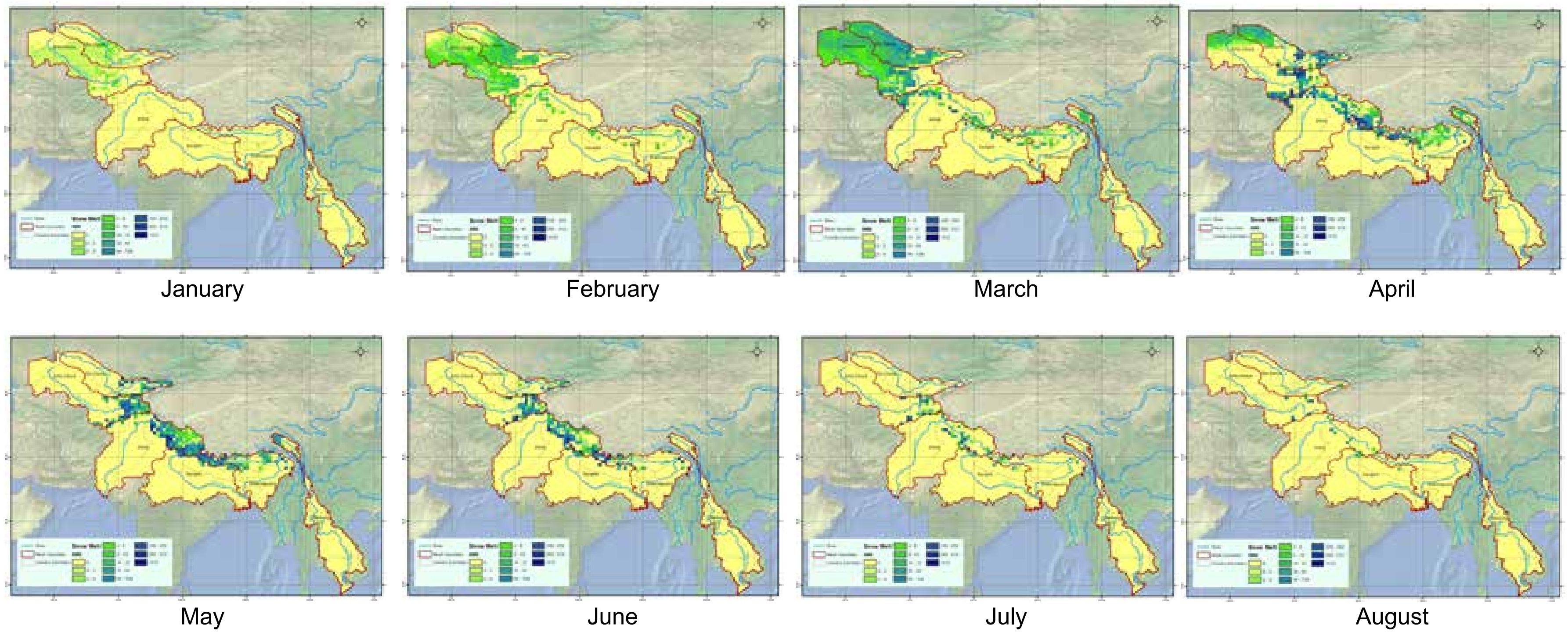
Basin	Specific glacier runoff renewable component (mm/year)	Specific mass-loss rate in 1961-1990 nonrenewable component (mm/year)	Glacier-covered area in 1961-1990 (km^2)	Specific mass-loss rate in 2001-2010 nonrenewable component (mm/year)	Glacier-covered area in 2001-2010 (km^2)	Ice loss between 1961-1990 and 2001-2010 (km^3)
INDUS	1,200	300	27,759	550	21,193	400
GANGES	1,100	400	12,541	600	9,012	320
BRAHMAPUTRA	800	250	16,247	350	14,020	170
AMU DARYA	1,200	300	11,101	500	8,736	150
SYR DARYA	1,050	300	2,522	500	1,967	25
MEKONG	1,100	300	316	500	235	7
Data accuracy (%)	$\pm$30	$\pm$30	$\pm$5	$\pm$30	$\pm$5	$\pm$50

TABLE 5. Simulated mean annual glacier runoff components.

Basin	Glacier runoff components		Total glacier runoff (km^3)	Total glacier runoff contribution to MAF (%)
	Renewable (km^3)	Nonrenewable (km^3)		
1961-1990				
INDUS	33.0	8.14	41.2	18
GANGES	11.0	4.74	15.7	4
BRAHMAPUTRA	12.7	4.29	17.0	2
AMU DARYA	16.1	3.18	19.3	25
SYR DARYA	2.65	0.73	3.38	9
MEKONG	0.25	0.12	0.37	0.1
2001-2010				
INDUS	24.5	11.62	36.1	15
GANGES	8.1	6.95	15.0	3
BRAHMAPUTRA	10.6	5.05	15.7	2
AMU DARYA	13.3	4.63	18.0	23
SYR DARYA	2.21	0.94	3.15	8
MEKONG	0.18	0.13	0.32	0.1

The results of the assessment of the contribution of seasonal snowmelt to basins' MAF are presented in Table 6. The difference between our assessment of snowmelt contribution to MAF in the HKH region and that by Immerzeel et al. (2009, 2010), i.e., 74 km^3 (32% of MAF), 20 km^3 (4%) and 94 km^3 (14%) in the Indus, Ganges and Brahmaputra basins, respectively, is especially high for the Brahmaputra Basin. It may be attributed to the use of different climatological data sources, under-accounting of sublimation and losses to groundwater aquifers in the Upper Brahmaputra Basin by Immerzeel et al. (2009, 2010). The assessment presented here makes the first systematic attempt to account for losses to groundwater aquifers from surface snowmelt and to subtract snowmelt component of glacier runoff from the total basin snowmelt.

FIGURE 8. 1961-1990 mean monthly surface snowmelt yields for the period from January to August.



Data source: The University of Delaware Terrestrial Water Budget Archive (http://climate.geog.udel.edu/~climate/; Willmott and Matsuura 2006).

TABLE 6. Seasonal snowmelt contribution to MAF.

Basin	1961-1990			2001-2010		
	Total seasonal snowmelt (km^3)	Contribution to MAF		Total seasonal snowmelt (km^3)	Contribution to MAF	
		(km^3)	(%)		(km^3)	(%)
INDUS	66.5	43.5	19	55.8	37.6	16
GANGES	13.2	6.9	2	10.5	5.6	1
BRAHMAPUTRA	25.8	15.6	2	23.4	14.3	2
AMU DARYA	54.8	35.1	45	50.9	32.5	42
SYR DARYA	35.4	27.3	70	27.6	19.7	50
MEKONG	2.1	1.2	0.3	2.4	1.4	0.3

The Hydrological Role of Glaciers and Snow in the Study Basins

The assessment of frozen water resources and meltwater contribution to the flow for two time slices, 1961-1990 and 2001-2010, summed up in Table 7, indicates that the hydrological role of glaciers and seasonal snow varies significantly from basin to basin. In the Aral Sea basins, where snow cover at its maximum annual extent covers major parts of the basins, snow extent contribution to the flow by far outweighs that of glaciers, making 45% and 70% of MAF. Glacier runoff contribution to the flow makes 25% in the Amu Darya Basin (the highest among the study basins) and 9% in the Syr Darya Basin. In this arid region, the hydrographs are shaped mainly by the meltwater components. Meltwater resources are of high importance in the Aral Sea region because annual maximum of precipitation occurs in winter, hence summer flow depends a lot on the storage capacity of snow and glaciers (Kaser et al. 2010).

TABLE 7. Summary of the recent changes in the extent of glaciers and seasonal snow and their contributions to MAF.

Basin	Part of basin area (%) covered by		Contribution to MAF (%)	
	Glaciers	Seasonal snow	Glacier runoff	Seasonal snowmelt
1961-1990				
INDUS	2.6	28	18	19
GANGES	1.2	6	4	2
BRAHMAPUTRA	2.7	27	2	2
AMU DARYA	1.7	66	25	45
SYR DARYA	0.6	90	9	70
MEKONG	0.04	6	0.1	0.2
2001-2010				
INDUS	1.8	25	15	16
GANGES	0.9	6	3	1
BRAHMAPUTRA	2.2	26	2	2
AMU DARYA	1.3	61	23	42
SYR DARYA	0.4	76	8	50
MEKONG	0.02	6	0.1	0.3

In the Ganges and Mekong basins, the hydroclimatology is opposite to the Aral Sea region. Lavish monsoon precipitation occurs here in summer, with maximum rainfall at elevations below 3,000 m, i.e., just below the glacier occurrence zone. Summer precipitation almost solely determines MAF volume and shape of the 'natural' hydrograph (Kaser et al. 2010). Maximum seasonal snow extent in these two basins makes just 6% of the entire basin area, and its contribution to MAF is insignificant (being a mere 2% and 0.2%, respectively), reaching significant levels only in the headwaters (Rees and Collins 2004; Bolch et al. 2012). Glacier runoff in the Mekong also makes a negligible contribution to MAF (0.1%). In the Ganges Basin, glacier contribution to MAF is 4% (Table 7). However, its mid- and late-summer maximum coincides with the peak of rain contribution to the flow, and, therefore, the overall hydrological role of glaciers is as insignificant as that of the snow. Overall, meltwater components of the flow in the Ganges and Mekong are of relative importance only at the upstream sub-catchment level at high elevations.

Situation is similar in the Brahmaputra Basin, despite a sharp contrast of physical settings in the upper and lower parts of the basin. The dominant part of basin's streamflow is formed in the lower parts of the basin, i.e., in the Southeastern Tibet and Eastern Himalaya, both heavily influenced by summer monsoon rains. About 75% of the basin's glaciers are located here, and, similarly to Ganges and Mekong, glacier runoff, which peaks in summer, gets almost 'lost' in the overall high summer flow. The high-elevated terrain in the headwaters of Brahmaputra, i.e., Southwestern Tibet located in the orographic shade of the Himalaya, is cold and arid. The remaining 25% of basin's glaciers located here contribute little to the total basin's flow because of very low glacier mass turnover in this climate. Besides, sublimation in the Upper Brahmaputra is the highest among all the study basins, because of the low air humidity and prevalence of cloudless weather conditions (Kotlyakov 1997). Sublimation plays an important role in overall glacier and seasonal snow ablation, thus reducing the meltwater discharge from glaciers and seasonal snow. Seasonal snow in the Brahmaputra Basin covers, at its annual maximum, approximately one-quarter (27%) of the entire basin, i.e., the part of the basin located within Tibetan Plateau and in the high elevation zones in Himalaya. However, the overall contribution of the snowmelt to MAF of Brahmaputra is a mere 2%, because the amount of precipitation falling as snow is insignificant compared to summer rains.

Precipitation in the Indus Basin is more evenly distributed between the seasons, but is highly variable spatially – similarly to Brahmaputra and Amu Darya, where annual precipitation in some catchments is tenfold (3,000 mm) of that in the other glacier-covered parts of the basin (300 mm). About half of the total basin flow originates from the monsoon-influenced West Himalaya, where about 25% of the basin's glaciers are located. The central part of the Upper Indus Basin has a unique combination of factors favorable for sustaining large glaciers: extremely cold and relatively humid. Although it is to a large degree screened from the monsoonal influence by the West Himalaya ranges in the southwest, westerly cyclone intrusions bring a lot of snow to the orographic trap formed by the Hindu Kush to the north, Karakoram to the east and West Himalaya ranges to the south. A very active glacier regime, high rates of mass turnover, and sheer volume and areal extent of glacier ice, similar to that in Amu Darya Basin, is responsible for the very high glacier runoff yields from almost all the glaciated sub-catchments, apart from the uppermost part of the Indus Basin, stretching into arid Western Tibet. This part of the basin screened by Karakoram from the western intrusions and by Himalaya from the southern monsoonal influence is in a deep orographic shadow with respect to precipitation. Similarly to the Upper Brahmaputra Basin, the glaciers in this part of the Indus Basin generate little runoff due to low mass turnover rates. Seasonal snow covers 28% of the Indus Basin and contributes 19% to MAF. Glacier runoff and seasonal snowmelt play a very important role in shaping the hydrograph in the Upper Indus Basin, but rapidly lose this role in the middle stream, where the Indus receives tributaries originating from Western Himalaya.

The share of the nonrenewable component in total glacier runoff of the study basins in the baseline period (1961-1990) was 16-30%, being the lowest in the Amu Darya and the highest in the Ganges Basin. The changes between 1961-1990 and 2001-2010 are remarkable. Because of the overall reduction of glaciated areas, the relative shares of renewable and nonrenewable components in glacier runoff have changed in the opposite directions: the former has reduced and the latter has increased compared to the baseline period. However, according to the simulation presented in this report, the increase of the nonrenewable component in none of the study basins is large enough to compensate for the reduction of the renewable component of glacier runoff. As a result, there was an overall decrease by 4-15% of total glacier runoff contribution to MAF, with the Indus Basin at the upper end of this range and the Ganges Basin at the lower end.

Total values of seasonal snow contribution to MAF between the two time slices, i.e., 1961-1990 and 2001-2010, have decreased by 10-30% due to overall reduction of stable seasonal snow cover extent, its duration and water storage capacity in all the basins except Mekong (Savoskul and Smakhtin 2013). Snow contribution to MAF has decreased drastically only in the Syr Darya Basin, where it dropped to 50% from 70% in the baseline period. In the Indus and Amu Darya basins, the changes are within 3%. In the Ganges and Brahmaputra, the changes are insignificant, since snow here does not play a prominent role in the river water balances. In the Mekong Basin, detection of the recent changes in seasonal snowmelt is practically beyond the method's accuracy range.

Climate Change Impact on the Meltwater Resources

All the methods of glacier runoff and seasonal snowmelt modeling described above are suitable for the assessment of CC impacts on meltwater. Application of these methods faces the same dilemma of being physically sound and accurate, on the one hand, and being representative of a large-scale territory, on the other (Lamadrid and MacClune 2010). An additional challenge is posed by the uncertainties of CC projections (Bolch et al. 2012).

Temperature-index approaches of glacier and snowmelt appear to be suitable for the purposes of CC-impact assessments, since they are forced by air temperature, one of the principal variables of outputs from global circulation models (GCM). However, as in the case of the current glacier runoff assessment, reliability of simulations depends on the availability of data for model validation and calibration. Assessment of seasonal snowmelt contribution to the flow at the basin scale is commonly based on temperature-indexation coupled with assessment of future snow cover extent and duration. Fully distributed or semi-distributed models utilizing the elevation band approach to calculate melt yields from different elevations and various streamflow routing procedures are widely used at present (Barnett et al. 2005; Immerzeel et al. 2009; Bocchiola et al. 2011; Mukhopadhyay and Dutta 2010).

Judging by the number of publications on CC-related topics, it appears that the research in High Asia is concerned much more with CC impacts than with objects of the impact. Yet, understanding of the expected basin-scale changes in glacier runoff in response to CC, remains largely unclear (Armstrong 2010; Viviroli et al. 2011). Recent politicization of CC-related science definitely facilitated the research in this field, but in a very selective way. Since the problem of future water availability in the HKH and Aral Sea regions came into the spotlight, the studies focused on simulating outflow from glaciated catchments by far out-number those dealing specifically with modeling future glaciers' state and future glacier runoff. Glacier runoff modeling comes into the big picture just as a component of the total flow simulation, which often negatively affects the quality of both. The simulations of glacier changes in large-scale hydrological models tend to be done in a rather simplistic way, if not neglected entirely (Lamadrid and MacClune 2010; Bolch et al. 2012).

A thorough overview of 68 hydrological CC-impact assessments in glaciated basins in High Asia is given by Lamadrid and MacClune (2010). A closer look at those works indicates that the field is dominated by studies simulating seasonal snowmelt inseparably from glacier runoff. Exceptions include: Rees and Collins 2004, 2006; Arora et al. 2008; Singh and Bengtsson 2004; Singh et al. 2008; Konz et al. 2007; Rathore et al. 2009; and Kumar et al. 2010. Future glacier-melt in these studies has been estimated exclusively by temperature-index methods, which, as was discussed above, have significant uncertainties even for baseline conditions. None of the 68 publications in the list of Lamadrid and MacClune (2010) elaborates on calibration and verification of the glacier-melt module or provides an explicit explanation of how it works.

Use of ill-defined scenarios of future climates or of future glacier status is another major problem affecting quality of the available assessments of future changes in meltwater contribution to flow. Investigation of potential effects of deglaciation on MAF and flow seasonality is commonly done under a set of scenarios of the future glacier reduction in several decremental steps, e.g., 90, 50 and 10% of the currently glaciated area (Akhtar et al. 2008; Rees and Collins 2006; Hagg et al. 2007; Immerzeel et al. 2009, 2010). Physical plausibility of those scenarios, however, might be questionable, as the following discussion indicates.

From the basin water balance perspective, glaciers and seasonal snow cover are transient water storages for precipitation with a capacity for a seasonal and intra-annual delay of precipitation entry into the streamflow. Therefore, their withdrawal from a certain area implies first and foremost the loss of flow regulation capacity in basin's headwaters. However, it appears that in most scenarios when a glacier reduction is considered, the authors 'remove' the glaciers from a basin together with the precipitation, which sustains them at present. From the basic glaciological knowledge, it is entirely implausible. Assuming no drastic changes in the precipitation regime, the overall reduction of glaciated and snow-covered areas is supposed to result in the reduction of meltwater components and at the same time in the corresponding increase of the rain contribution to MAF (Barnett et al. 2005). Thus, the principal CC impact on hydrology of basins containing glaciers is growth of importance of liquid precipitation in shaping the hydrograph. The only direct effect of glaciers' reduction on MAF is related with the changes in the nonrenewable component of glacier runoff (Dyurgerov et al. 1995; Xie et al. 2006). Among the study basins (Table 5), the nonrenewable component of glacier runoff has increased in the past 50 years, by maximum 1-2% of MAF. Hence, it is unlikely that it will have profound effects on MAF in the future either.

The study of Akhtar et al. (2008) demonstrates that non-plausible scenarios tend to yield a drastic decrease in meltwater resources, whereas scenarios which incorporate plausible changes in temperature and precipitation under hypothetic glacier reduction yield moderate CC impacts on MAF. However, use of plausible scenarios is rather an exception than a rule. For instance, the study of Rees and Collins (2004) is the only one to date that makes a systematic effort to simulate future runoff across all three basins in the HKH region under a single set of future climate scenarios for the next 100 year runs. The source uses a model with incorporated glacier-melt module and provides the results of flow simulations at six flow stations in the Indus Basin, seven in the Brahmaputra Basin and eight in the Ganges Basin. The main conclusion of the authors that, "the catastrophic water shortages forecast by some experts are unlikely to happen for many decades, if at all" (Rees and Collins 2004, iv-v) appears to be well justified. Yet, this cannot be said with regards to the simulated future streamflow in the upper parts of the basins.

Changes in annual upstream flow in the course of the next 100 years, suggested by Rees and Collins (2004), are extremely high: within ±90% from its baseline value for the Upper Indus Basin, between an increase by 33% and then down by 50% for the Upper Ganges Basin and a noticeable streamflow decline in the headwaters of Brahmaputra. This simulation scenario apparently implies that precipitation, which sustains glaciers at present (e.g., approximately 25 km^3 in the Indus Basin, according to data presented in Table 5), in the future would be entirely withdrawn from the areas, which are presently under glaciers. Thus, the plausibility of the scenario used in this simulation (Rees and Collins 2004) and hence of the simulation results are equally questionable. Another shortcoming of this study (Rees and Collins 2004) is the use of a single GCM-based scenario, which contradicts recommendations by Intergovernmental Panel on Climate Change (IPCC) to apply outputs from several models in order to make the scenarios representative of the entire range of projected changes for future climate (IPCC 2001; Cruz et al. 2007). The use of a crude source for data on glacier extent (Digital Chart of the World - http://www.princeton.edu/~geolib/gis/dcw.html) too is likely to increase the uncertainty of the simulation carried out by Rees and Collins (2004).

Study of Bocchiola et al. (2011) is aimed at predicting the hydrological regime in 2050-2059 in the poorly gauged Shigar catchment, which is nested in the Upper Indus Basin, contains approximately 8% of glaciated area of the entire basin and has 37% ice-coverage of the catchment area. The main scenario of the future climate here, too, is based on the outputs from a single GCM. The simulation of the flow from the catchment suggests either its increase up to 218% of the present (2000-2009) value or a decrease down to 78%, depending on the sub-scenario of the future glacier extent, for which arbitrarily assigned values of 100%, 90%, 75% and 50% of its present status are used. Similar to Rees and Collins (2004), Bocchiola et al. (2011) do not state explicitly what will happen to precipitation that, at present, falls on the glaciated areas and seemingly just omit it from future basin water budget.

Likewise, Immerzeel et al. (2010) run SRM model under 'best-guess scenario' (25% reduction of glacier-covered areas combined with A1B SRES CC scenario for the time slice 2046 to 2065) to examine the impact of the reduced glacier and snow cover on the hydrological regimes in the upper parts of the basins. The simulation yielded the following reduction rates for MAF: the Upper Indus - 8.4%, the Ganges - 17.6%, Brahmaputra - 19.6%, all relative to 2000-2007. However, Immerzeel et al. (2010) too do not explicitly define what changes in precipitation are assumed by their CC scenario. Another example is research carried out by Rathore et al. (2009), where the future scenario for 2040 is defined by air temperature rise of 1 ^{o}C and modelled changes in snow and glacier extent relative to present, but the scenario construction is not supported by discussion of expected changes in precipitation. Future changes in flow from Wangar Gad catchment (the Indus Basin) as suggested by SRM run under this scenario, imply an overall flow decrease by 8-28% (Rathore et al. 2009).

Similarly, APN (2005) simulation of future flow in the Upper Indus Basin is carried out under a hypothetical CC scenario assuming a 3 ^{o}C increase in air temperature and 50% reduction in glacier area, and no specification regarding future precipitation. The simulation results suggest that "15% reduction in annual flows, it would also result in a considerable alteration of the intra-annual pattern of flows" (APN 2005, 66).

The use of CC scenarios with properly defined precipitation changes yields more realistic results. Simulation of the streamflow in the Upper Indus Basin for 2070-2090 relative to 2000-2005 under PRECIS regional CC model and with an assumption of 50% reduction in the glacier area, suggests just a slight overall increase of flow by 7%, with the following changes of contribution to MAF from different sources: snowmelt - decrease from 40% to 32%, glacier runoff - decrease from 32% to 23%, and rain - increase from 28 to 40% (Immerzeel et al. 2009).

In the Aral Sea region, the current state of the art with regards to CC-impact assessments for glaciers is slightly better compared to the HKH basins. The CC-impact simulation for the entire Tien Shan Mountains by Aizen et al. (2007, 1), based on glacier mass budget approach, suggests that, “an increase in mean air temperature of 4 °C and precipitation of 1.1 times the current level could increase ELA by 570 m during the 21st century. Under these conditions, the number of glaciers, glacier covered area, glacier volume and glacier runoff are predicted to be 94%, 69%, 75% and 75% of current values. The maximum glacier runoff may reach as much as 1.25 times current levels while the minimum will likely equal zero.”

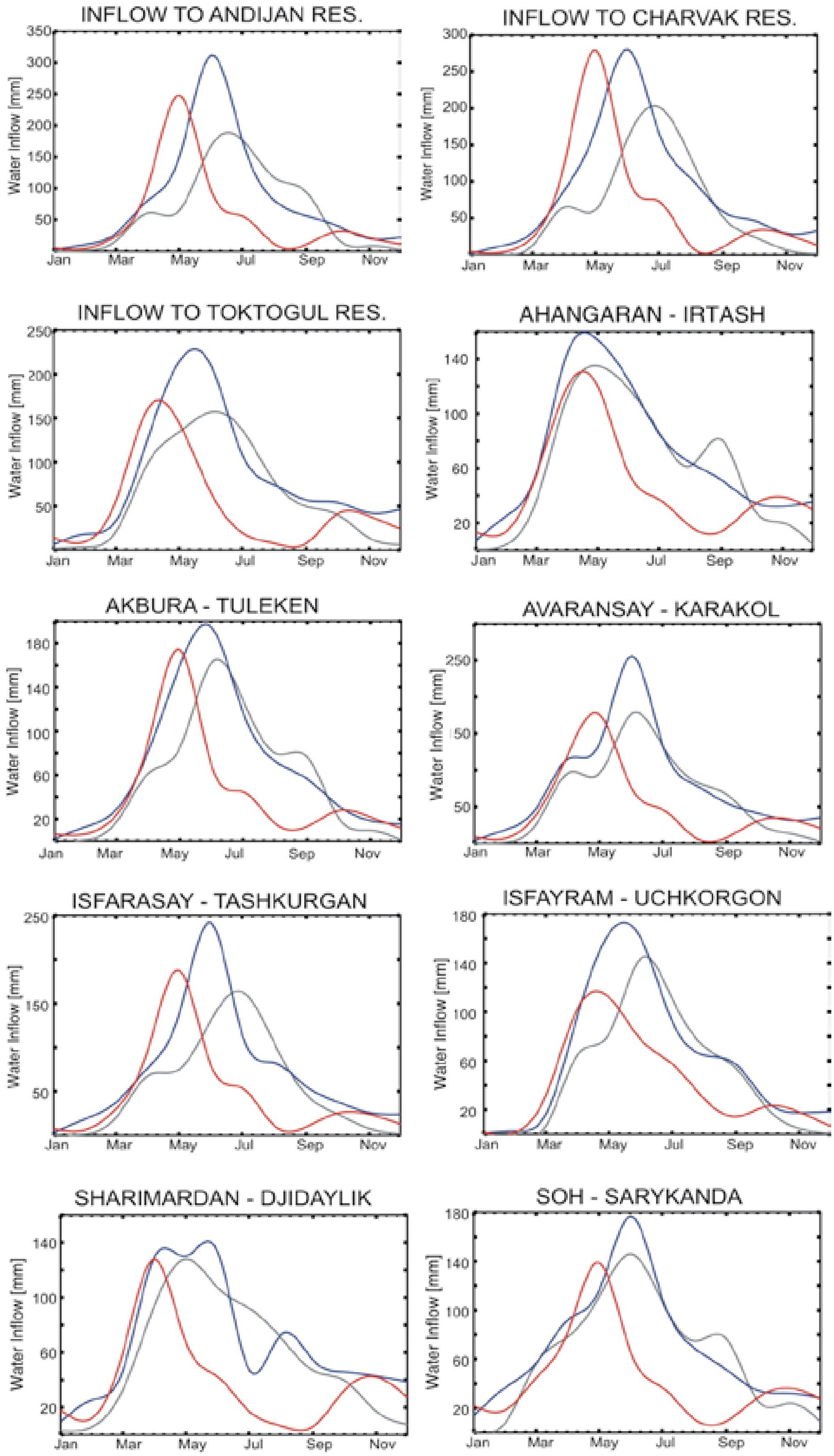
Water availability in 10 major sub-catchments of the Syr Darya Basin under HadCM3 and GFDL99-based scenarios for 2070-2099, has been assessed by Savoskul and Shevnina (2011) through the application of a Water Evaluation and Planning (WEAP) model, fed with the outputs from semi-distributed streamflow model, which has separate modules for glacier runoff and snowmelt contribution to the flow. The selected CC scenarios represent the range of the projected CC in the region by the core GCM included in Cruz et al. 2007. Glacier runoff assessment in this study is run in three steps: future ELA modeling based on full glacier budget simulation; glacier area change simulation; and glacier mass loss assessment based on simulated glacier area reduction. The results of the simulation suggest an overall increase of streamflow in the Syr Darya Basin by 20-30% under a downscaled GFDL99-based scenario (3-4 °C increase in air temperature and 5-10% increase in precipitation), and no significant changes of flow under a HadCM3-based regional scenario (air temperature increase by approximately 5-6 °C and precipitation decrease by 15-20% relative to baseline 1961-1990). The simulated changes in hydrographs for the major tributary systems in the Syr Darya Basin are illustrated in Figure 9.

In the Upper Amu Darya Basin, future glacier extent and water availability in Pyanj catchment, which has just 3% of the glaciated area of the entire basin, is assessed by Hagg et al. (2011, 2013) under two scenarios for 2050 suggesting a temperature rise of 2.2 °C and 3.1 °C and no changes in precipitation. The results show the reduction of the glacier extent by 36% and 45%, respectively, under the two scenarios. Hydrological simulation indicates that effects of reduced glacier area and increased specific glacier runoff on the net glacier runoff value counterbalance one another. Therefore, MAF from the catchment remains at the same level (Hagg et al. 2011, 2013). Observations for the period 1930-1990 in Northern Tien Shan (Vilesov 1999) also indicate that the glacier runoff remained virtually unchanged in the past 60 years, despite a reduction in the glacier area from 12.7% to 7.8% in the study area.

Small-scale assessments in the study basins (Braun et al. 1993; Rana and Nakawo 1997; Singh and Bengtsson 2003, 2004, 2005; Hagg and Braun 2006; Hagg et al. 2007; Glazirin 2009) confirm that the major CC impact on the flow from glaciated catchments is the change in its seasonality due to the reduction of glacier-covered area. The changes in total MAF are generally attributed not so much to the effects of deglaciation as to the projected changes in precipitation and evapotranspiration (Kundzewicz et al. 2008).

For the assessment of the changes in snowmelt-dominated flow, conceptual models and temperature index-based models have been shown to perform well (Hock 2003). Typical for these applications is the use of synthetic CC scenarios with arbitrarily chosen incremental changes in air temperature (+1, +2, +3 °C) and precipitation (±10%, ±20%) relative to baseline values (e.g., Singh and Bengtsson 2004; Arora et al. 2008). The CC impact on seasonal snow cover in the study basins is addressed in a number of publications (Aizen and Aizen 1996; Singh and Kumar 1996; Singh and Bengtsson 2003; Immerzeel et al. 2009; Gosain et al. 2010; Tahir et al. 2011; Singh and Jain 2003; Singh et al. 2008). Based on these studies, the dominant tendency in seasonal snowmelt response to global warming is a shift of the beginning of the snowmelt period and its peak to earlier dates, and an increase of the overall duration of the snowmelt period. The likely changes in the overall volume of snowmelt for the study basins

FIGURE 9. Simulated changes in streamflow in the upper reaches of the Syr Darya Basin. Grey (dotted) line – baseline (1961-1990), blue line – scenario based on GFDL99 outputs, red line – scenario based on HadCM3 outputs.



Data source: Savoskul and Shevnina 2011.
Note: RES. = Reservoir.

under GCM-based CC scenarios are, however, not quantified separately from glacier-melt in any publication known to the authors of this report.

A review of publications concerned with future changes in water availability due to CC in High Asia would not be complete without mentioning 'assessments' relying on poorly verified sources. It appears that an apocalyptic vision expressed in Cruz et al. (2007, 498), "The current trends of glacier-melts suggest that the Ganga, Indus, Brahmaputra and other rivers that criss-cross the northern Indian plain could likely become seasonal rivers in the near future as a consequence of climate change…," had a profound influence on subsequent studies. Despite this statement being admitted as a typing error (IPCC 2010; Cogley et al. 2010), it is still reiterated in NGO reports, based on what can be termed here a compilation of anecdotal evidence: "Rivers dependent on glacial melt from mountain ecosystems… will be altered or dry up altogether." (ADB 2009) or "… water flowing from the Himalayas to the plains, and then on to the Indian subcontinent… supports approximately more than a billion people. Decreases in snow accumulation and glacial retreat might lead to acute water shortages in the future" (http://hpccc.gov.in/chellangesSnow.aspx).

The scenario of major Asian rivers drying up altogether as the result of glacier reduction, which will cause acute water shortages in the future, does not stand against the evidence presented in this report - that glacier contribution is a minor item in river water budgets in the Ganges and Brahmaputra basins (Table 5). This is confirmed by a number of previous studies (e.g., Rees and Collins 2004; Alford et al. 2009), or by Singh and Bengtsson (2004), "The impact of climate change was found to be more prominent on seasonal rather than annual water availability."

A physically plausible analogue of a future deglaciated state of a major river basin in the monsoon-dominated region is the Mekong Basin, where total meltwater contribution to MAF is 0.5% (Tables 5-7). Certainly, the likelihood of the Ganges and Brahmaputra becoming seasonal rivers is not higher than that of the Mekong in its current status. Moreover, since precipitation in the Indus Basin is unlikely to decrease drastically under any known future climate projections, but most likely will increase (Cruz et al. 2007; Eriksson et al. 2009; Gosain et al. 2010) and because orographic precipitation effect too is unlikely to be arrested, the scenario of the Indus Basin drying up seems to be highly unrealistic either.

Gosain et al. (2010) present a large-scale comprehensive assessment of future water availability in the entire Brahmaputra Basin for the end of the century (2070-2099). The impacts of CC on snowfall, snowmelt, surface flow and groundwater recharge are modelled and reported in this publication under a number of CC scenarios (HadRM3, GHG-A2 and GHG-B2), representative for the entire range of future CC projections for that region. Streamflow simulation of Gosain et al. (2010) suggest an overall water yield increase by 23-38% under increase of precipitation by 14-22% and moderate air temperature rise by 2.5-4 °C.

However, even the most credible sources available to date do not provide enough data for drawing conclusive statements about possible CC impacts on glacier runoff and seasonal snowmelt in all of the study basins (Qiu 2008, 2010; Absar 2010; Archer et al. 2010; Armstrong 2010; Malone 2010; Schiermeier 2010; Bolch et al. 2012). The main reason is incompatibility of most assessments due to considerable differences in adopted scenarios and methods. An explicit numerical assessment of the likely changes of glacier runoff and seasonal snowmelt as separate components under CC still awaits a more consistent and well-coordinated modeling effort. However, some conclusions on the pattern of physically plausible response of hydrological systems to CC on glaciers and seasonal snow in High Asia may be formulated with certainty:

- The presence or absence of glaciers and seasonal snow in the mountains does not change the amount of precipitation received by the upper mountain belt; it determines the timing of its release into streamflow, i.e., the type of hydrological regime.
- Main changes in MAF of the major rivers will be determined by future changes of

precipitation and evapotranspiration due to the rise of mean air temperature.

- Glaciers and seasonal snow under CC should be perceived not as water resources as such, but rather as natural water reservoirs with gradually diminishing storage and flow regulation capacity.
- Combined effect of the reduction of glacier area and seasonal snow extent on the seasonality of flow from the alpine catchments will be characterized by an increase of the magnitude of the short-term flow variability, in particular, an increase of autumn and winter flow, shift of late spring-early summer peak to earlier dates and possible decrease of mid-late summer flow (assuming no changes in precipitation). Hydrological regimes will be gradually changing from glacio-nival to fluvial, i.e., dependent primarily on rainfall.
- Since glaciers currently play a prominent role in smoothing inter-annual flow variability, the latter is likely to increase as a consequence of glacier area reduction.
- The increment of total MAF due to glacier mass loss, i.e., nonrenewable component of glacier runoff is a minor item in major rivers' water budget. If precipitation regime would not change, MAF is likely to slightly increase in the next decades and then to diminish as a consequence of overall reduction of glacier-covered area.

Conclusions

1. Hydrological role of meltwater resources in Indus, Ganges, Brahmaputra, Syr Darya, Amu Darya and Mekong river basins is, for the first time, comprehensively assessed at the basin scale. The changes in the meltwater resources between baseline (1961-1990) and current (2001-2010) states are analyzed using the following characteristics: specific glacier runoff (average depth of annual discharge from glacier-covered area); basin total glacier runoff; shares of renewable and nonrenewable components in glacier runoff; total seasonal surface snowmelt; total volume of seasonal snowmelt from non-glaciated areas entering the streamflow of the major rivers after losses to groundwater aquifers; and eventually contribution of glacier runoff and seasonal snowmelt to MAF in each basin.
2. Critical review of methods applicable to basin-scale assessments of meltwater discharge suggests that in glacier runoff simulations, the accuracy of temperature-index methods may be as low as ±50-100%. Glacier mass budget-based methods and hydrograph separation techniques are more suitable for basin-scale assessments, offering the highest currently possible accuracy of ±30%, with both methods performing well in semi-distributed models. Temperature-index methods are more appropriate for seasonal snowmelt runoff assessment in fully and semi-distributed models and also in models based on elevation-belt approach.
3. It is proposed to compare the outcomes of the future glacier runoff assessments using specific glacier runoff (average depth of annual discharge from glacier-covered area) as a reporting standard. This would help make the results of large-scale assessments compatible. Since glacier runoff depends mainly on regional precipitation, estimates of actual snow accumulation at ELA, made with consideration of wind and snow avalanche factors in snow redistribution, should be used as a proxy for the specific glacier runoff under steady-state conditions, i.e., for the

robust estimate of the renewable component of glacier runoff. Estimates of annual glacier mass loss rates should be used as the basis for the assessments of the nonrenewable component of total glacier runoff.

4. Based on a thorough literature review, the pattern of regional variability of specific glacier runoff can be described as follows. In dry areas, such as the Tibetan Plateau or interior Pamir and Tien Shan, where the upper parts of most study basins are located, specific glacier runoff is expected to be around 300-800 mm/year. In the areas with abundant precipitation, such as the south-facing parts of Himalaya and the front ranges of Karakoram, Pamir and Tien Shan, i.e., in the major parts of the Ganges and Mekong basins and lower parts of the other study basins, specific glacier runoff is expected to be around 1,500-2,500 mm/year. These values may be used as reference for future studies.

5. For the first time, it is estimated that in the reference period of 1961-1990, total glacier runoff was 41 km^3 in the Indus Basin, and 16 km^3, 17 km^3, 19 km^3, 3.4 km^3 and 0.4 km^3 in the Ganges, Brahmaputra, Amu Darya, Syr Darya and Mekong basins, respectively. In the more recent period of 2001-2010, total glacier runoff was reduced to 36 km^3, 15 km^3, 16 km^3, 18 km^3, 3.2 km^3 and 0.3 km^3, respectively, in those six basins. Basin total seasonal snowmelt from non-glaciated areas was 44 km^3, 7 km^3, 17 km^3, 35 km^3, 27 km^3 and 1.2 km^3, respectively, and corresponding values have changed over the course of the past 50 years to 38 km^3, 6 km^3, 14 km^3, 33 km^3, 20 km^3 and 1.4 km^3, respectively, of which 25-50% is lost to groundwater aquifers and only the remaining 50-75% enter the streamflow.

6. The contribution of meltwater components to MAF and respective shares of basin total glacier runoff and seasonal snowmelt from ice-free areas vary a lot depending on regional hydroclimatology. In the baseline period of 1961-1990, meltwater components together contributed to MAF: 37% - in the Indus, 6% - in Ganges, 3% - in Brahmaputra, 69% - in Amu Darya, 79% - in Syr Darya, and 0.4% in Mekong Basin. The ratios of glacier runoff to seasonal snowmelt from ice-free areas in total meltwater contribution to MAF were: 49:51 (Indus); 50:50 (Ganges); 71:29 (Brahmaputra); 35:65 (Amu Darya); 11:89 (Syr Darya); and 22:78 (Mekong). The meltwater components play a dominating role in the hydrological regime of the Amu Darya and Syr Darya basins, a prominent role in the Indus, a minor role in the Ganges and Brahmaputra, and are insignificant in the Mekong Basin. The importance of meltwater components in regional water cycle decreases from basins where winter precipitation is significant in relation to summer precipitation, to the basins with dominant role of summer monsoons in total annual precipitation.

7. From 1961-1990 to 2001-2010 the total values of meltwater components decreased by 6-25% in all the basins, except Mekong, where snowmelt increased due to a slight increase in the snow cover extent. Reduction of glacier and seasonal snow extent in the past 50 years resulted in the decrease of meltwater contribution to the annual flow by 5% in the Indus and Amu Darya and by 20% in the Syr Darya Basin, which was most likely compensated by the corresponding increase in the contribution from rain. The changes of meltwater contribution to flow due to the overall reduction of glacier and seasonal snow extent have been significant only in the basins where meltwater components play an important role in the hydrological regime.

8. The glacier runoff simulation results suggest that relative shares of renewable and nonrenewable components in total glacier runoff have undergone a remarkable change: the nonrenewable component increased from

16-30% of total glacier runoff in 1961-1990 to 26-46% in 2001-2010 in all the study basins. However, the increase of nonrenewable runoff in none of the basins has been large enough to overweigh the decrease of the renewable component of glacier runoff due to overall reduction of the glacier-covered area.

9. It is recommended to use plausible scenarios of future climate and environmental changes in studies aimed at assessing the impact of glacier and snow cover extent on hydrological regimes. A thorough review of published CC-impact assessments on hydrological regimes suggests that presence or absence of glaciers and seasonal snow in the mountains will not change the amount of precipitation received by areas where they are currently located. Glaciers and seasonal snow in CC-impact assessments should be perceived as natural water reservoirs with gradually diminishing storage and flow regulation capacity, both on intra-annual and inter-annual scale. Potential changes of precipitation regime coupled with effects of temperature rise on evapotranspiration will impact future hydrological regimes of the major rivers much more significantly, affecting both MAF and flow seasonality.

10. Long-term MAF in the study basins is likely to be affected marginally by the reduction of glacier and seasonal snow extent. The CC impact on the hydrological regime of the rivers, where meltwater components are important, will be related mainly to change of flow seasonality. In the arid Amu Darya, Syr Darya, Indus and Upper Brahmaputra basins, meltwater components will contribute less water to MAF in the late spring and summer, and more water in winter and early spring. In the monsoon-dominated Ganges, Lower Brahmaputra and Mekong basins, duration of low flow winter period is likely to be shortened, but the overall impact of changes of glacier and snow extent on hydrological regimes will be insignificant.

References

Absar, M. 2010. The impact of climate change on glaciers, water resources and livelihood of Pakistan. Islamabad: COMSTECH Secretariat. 51 pp.

ADB (Asian Development Bank). 2009. Building climate resilience in the agriculture sector of Asia and the Pacific. Philippines: Asian Development Bank. 313 pp. Available at http://www.adb.org/Documents/Books/Building-Climate-Resilience-Agriculture-Sector/Building-Climate-Resilience-Agriculture-Sector.pdf (accessed on May 13, 2011).

Aizen, V.B.; Aizen, E.M. 1994. Regime and mass-energy exchange of subtropical latitude glaciers under monsoon climatic conditions: Gongga Shan, Sichuan China. *Mountain Research and Development* 14(2): 101-118.

Aizen, V.B.; Aizen, E. 1996. Hydrological cycles on the North and South peripheries of mountain glacial basins of Central Asia. *Hydrological Processes* 11: 451-469.

Aizen, V.B.; Aizen, E.M. 1998. Estimation of glacial runoff to the Tarim River, Central Tien Shan. *IAHS Publications* 248: 191-199.

Aizen, V.; Aizen, E.; Kuzmichenok, V. 2007. Glacier and hydrological changes in the Tien Shan: Simulation and prediction. *Environmental Research Letters* 2: 1-10.

Aizen, V.B.; Aizen, E.M.; Melack, J.M. 1995. Climate, snow cover and runoff in the Tien Shan. *Water Resources Bulletin* 31(6): 1-17.

Aizen, V.B.; Aizen, E.M.; Melack, J.M. 1997. Snow distribution and melt in Central Tien Shan, Susamir Valley. *Journal of Arctic and Alpine Research* 29(4): 403-413.

Aizen, V.B.; Aizen, E.M.; Nikitin, S.A. 2002. Glacier regime on the northern slope of the Himalaya (Xixibangma glaciers). *Quaternary International* 97(8): 27-39.

Aizen, V.B.; Kuzmichenok, V.A.; Surazakov, A.B.; Aizen, E.M. 2006. Glacier changes in central and northern Tien Shan during the last 140 years based on surface and remote-sensing data. *Annals of Glaciology* 43: 202-213.

Aizen, V.B.; Loktionova, E. 1996. Computation of glacier runoff. *Journal of Hydrology* 186: 229-251.

Akhtar, M.; Ahmad, N.; Booij, M.J. 2008. The impact of climate change on the water resources of Hindukush-Karakoum-Himalaya region under different glacier coverage scenarios. *Journal of Hydrology* 355: 148-163.

Alford, D.; Armstrong, R. 2010. The role of glaciers in stream flow from the Nepal Himalaya. *The Cryosphere Discussions* 4: 469-494.

Alford, D.; Armstrong, R.; Racoviteanu, A. 2009. Glacier retreat in the Nepal Himalaya. The role of glaciers in the hydrologic regime of the Nepal Himalaya. Technical Report for the World Bank, South Asia Sustainable Development (SASDN) Environment and Water Resources Unit. Kathmandu: World Bank. 86 pp.

Ananicheva, M.D.; Davidovich, N.V. 1997. Vozmozhnie izmeneniya nekotorix harakteristik oledeneniya Pamiro-Alaya pri globalnom poteplenii klimata (Potential changes of some parameters of glacier system of Pamiro-Alay under global warming). *Data of Glaciological Studies* 83: 59-64 (in Russian).

Andermann, C.; Longuevergne, L.; Bonnet, S.; Crave, A.; Davy, P.; Gloaguen, R. 2012. Impact of transient groundwater storage on the discharge of Himalayan rivers. *Nature Geoscience* 5: 127-131.

APN (Asia-Pacific Network for Global Change Research). 2005. *Enhancement of national capacities in the application of simulation models for the assessment of climate change and its impacts on water resources and food and agricultural production*. Final Report for APN CAPaBLE Project: 2005-CRP1CMY-Khan. Islamabad, Pakistan: Global Change Impact Studies Centre. 97 pp.

Archer, D. 2003. Contrasting hydrological regimes in the upper Indus basin. *Journal of Hydrology* 274: 198-210.

Archer, D.R.; Forsythe, N.; Fowler, H.J.; Shah, S.M. 2010. Sustainability of water resources management in the Indus Basin under changing climatic and socio economic conditions. *Hydrology and Earth System Sciences* 14: 1669-1680.

Archer, D.R.; Fowler, H.J. 2004. Spatial and temporal variations in precipitation in the Upper Indus Basin, global teleconnections and hydrological implications. *Hydrology and Earth System Sciences* 8(1): 47-61.

Armstrong, R.L. 2010. The glaciers of the Hindu Kush-Himalayan Region. A summary of the science regarding glacier melt/retreat in the Himalayan, Hindu Kush, Karakoram, Pamir, and Tien Shan mountain ranges. USAID-ICIMOD, Technical Paper. Kathmandu: ICIMOD. 16 pp.

Arora, M.; Singh, P.; Goel, N.K.; Singh, R.D. 2008. Climate variability influences on hydrological responses of a Large Himalayan Basin. *Water Resources Management* 22: 1461-1475.

Bajracharya, S.R.; Shrestha, B. (Eds). 2011. The status of glaciers in the Hindu Kush-Himalayan Region. Kathmandu: ICIMOD. 140 pp.

Barnett, T.P.; Adam, J.C.; Lettenmaier, D.P. 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* 438: 303-309.

Benn, D.; Evans, D. 2006. Glaciers and glaciation. 2nd Edition. UK: Hodder Arnold Publication. 784 pp.

Bhutiyani, M.R. 1999. Mass-balance studies on Siachen glacier in the Nubra valley, Karakoram Himalaya, India. *Journal of Glaciology* 45(149): 112-118.

Bhutiyani, M.R.; Kale, V.S.; Pawar, N.J. 2007. Long-term trends in maximum, minimum, and mean annual air temperatures across the Northwestern Himalaya during the twentieth century. *Climatic Change* 85(1-2): 159-177.

Bocchiola, D.; Diolaiuti, G.; Soncini, A.; Mihalcea, C.; D'Agata, C.; Mayer, C.; Lambrecht, A.; Rosso, R.; Smiraglia, C. 2011. Prediction of future hydrological regimes in poorly gauged high altitude basins: the case study of the upper Indus, Pakistan. *Hydrology and Earth System Sciences Discussions* 8: 3743-3791.

Bolch, T.; Kulkarni, A.; Kääb, A.; Huggel1, C.; Paul, F.; Cogley, J.G.; Frey, H.; Kargel, J.S.; Fujita, K.; Scheel, M.; Bajracharya, S.; Stoffel, M. 2012. The state and fate of Himalayan glaciers. *Science* 336(6079): 310-314.

Bookhagen, B. 2012. Hydrology: Himalayan groundwater. *Nature Geoscience* 5: 97-98.

Bookhagen, B.; Burbank, D.W. 2010. Towards a complete Himalayan hydrologic budget: The spatiotemporal distribution of snowmelt and rainfall and their impact on river discharge. *Journal of Geophysical Research* 115(F3): 1-25.

Boscarello, L.; Ravazzani, G.; Rabuffetti, D.; Mancini, M. 2012. Integrating glaciers raster-based modelling in large catchments hydrological balance: the Rhone case study. *Hydrological Processes*. DOI: 10.1002/hyp.9588.

Bradley, R.S. 2011. Temperature changes at high elevations: the need for a satellite-linked high elevation observation network for Asia (CHENA). Materials of the International Symposium on Changing Cryosphere, Water Availability and Sustainable Development in Central Asia. Urumqi, China: Chinese Academy of Sciences. p. 116.

Braithwaite, R.J. 1985. Calculation of degree-days for glacier–climate research. *Zeitschrift fuer Gletscherkunde und Glazialgeologie* 20: 1-8.

Braithwaite, R.J.; Raper, S.; Chutko, K. 2006. Accumulation at the equilibrium-line altitude of glaciers inferred from a degree-day model and tested against field observations. *Annals of Glaciology* 43: 329-334.

Braun, L.N.; Grabs, W.; Rana, B. 1993. Application of a conceptual precipitation–runoff model in the Langtang Khola basin, Nepal Himalaya. *IAHS Publications* 218: 221-237.

Braun, L.N.; Hagg, W.; Severskiy, I.V.; Young, G. (eds.) 2009. Assessment of snow, glacier and water resources in Asia. IHP-HWRP 8, 186 pp.

Brown, G.H.; Tranter, M. 1990. Hydrograph and chemograph separation of bulk melt waters draining the upper Arolla Glacier, Valais, Switzerland. *IAHS Publications* 193: 429-437.

Brubaker, K.; Rangbo, A.; Kustas, W. 1996. Incorporating radiation inputs into the snowmelt runoff model. *Hydrological Processes* 10: 1329-1343.

Butt, M.J. 2012. Characteristics of snow cover in the Hindukush, Karakoram and Himalaya region using Landsat satellite data. *Hydrological Processes* 26(24): 3689-3698.

Cogley, J.G. 2010. A more complete version of the World Glacier Inventory. *Annals of Glaciology* 50(53): 32-38.

Cogley, J.G. 2011. Present and future states of Himalaya and Karakoram glaciers. *Annals of Glaciology* 52(59): 69-73.

Cogley, J.G.; Kargel, S.; Kaser, G.; van der Veen, C.J. 2010. Tracking the source of glacier misinformation. *Science* 327: 522.

Cruz, R.V.; Harasawa, H.; Lal, M.; Wu, S.; Anokhin, Y.; Punsalmaa, B.; Honda, Y.; Jafari, M.; Li, C.; Huu Ninh, N. 2007. Asia. In: *Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, eds., Parry, M.L.; Canziani, O.F.; Palutikof, J.P.; van der Linden, P.J.; Hanson, C.E. Cambridge, UK: Cambridge University Press. Pp. 469-506.

Dobhal, D.P.; Gergan, J.T.; Thayyen, R.J. 2008. Mass balance studies of the Dokriani Glacier from 1992 to 2000, Garhwal Himalaya, India. *Bulletin of Glaciological Research* 25: 9-17.

Dyurgerov, M.B. 2010. Reanalysis of glacier changes: From the IGY to the IPY, 1960-2008. *Data of Glaciological Studies* 108, 116 pp.

Dyurgerov, M.B.; Lu, S.; Xie, Z.-C. (Eds). 1995. Oledenenie Tian Shania (Glacier system of Tien Shan). Moscow: Institute of Geography Russian Academy of Sciences. 163 pp. (in Russian).

Eriksson, M.; Xu, J.; Shrestha, A.B.; Vaidya, R.A.; Nepal, S.; Sandstrom, K. 2009. *The changing Himalayas: Impact of climate change on water resources and livelihoods in the greater Himalayas*. Kathmandu: ICIMOD. 28 pp.

Forsythe, N.; Kilsby, C.G.; Fowler, H.J.; Archer, D.R. 2010. Assessing climate pressures on glacier-melt and snowmelt-derived runoff in the Hindu Kush-Karakoram sector of the Upper Indus Basin. International Symposium on Managing Consequences of a Changing Global Environment. Newcastle, UK: British Hydrolocal Society. pp. 1-8.

Fowler, H.J.; Archer, D.R. 2005. Hydro-climatological variability in the Upper Indus Basin and implications for water resources. *IAHS Publications* 295: 131-138.

Fowler, H.J.; Archer, D.R. 2006. Conflicting signals of climatic change in the Upper Indus Basin. *Journal of Climate* 19(17): 4276-4293.

Fujita, K.; Nakawo, M.; Fujii, Y.; Paudyal, P. 1997. Changes in glaciers in Hidden Valley, Mukut Himal, Nepal Himalayas, from 1974 to 1994. *Journal of Glaciology* 43(145): 583-588.

Fujita, K.; Nakazawa, F.; Rana, B. 2001a. Glaciological observation on Rikha Samba Glacier in Hidden Valley, Nepal Himalayas, 1998 and 1999. *Bulletin of Glaciological Research* 18: 31-35.

Fujita, K.; Kadota, T.; Rana, B.; Kayastha, R.B.; Ageta, Y. 2001b. Shrinkage of AX010 Glacier in Shorong region, Nepal Himalayas in the 1990s. *Bulletin of Glaciological Research* 18: 51-54.

Fujita, K.; Takeuchi, N.; Seko, K. 1998. Glaciological observations of Yala Glacier in Langtang Valley, Nepal Himalaya's 1994 and1996. *Bulletin of Glacier Research* 16: 75-81.

Glazirin, G.E. 1985. Raspredelenie i rezhim gornix lednikov. (Distribution and rezhime of alpine glaciers). Leningrad, USSR: Hydrometeoizdat. 116 pp. (in Russian).

Glazirin, G.E. 2009. Hydrometeorological monitoring system in Uzbekistan. In: *Assessment of snow, glacier and water resources in Central Asia*, eds., Braun, L.N.; Hagg, W.; Severskiy, I. V.; Young, G. IHP-HWRP, 8. pp. 65-83.

Gosain, A.K.; Shrestha, A.B.; Rao, S. 2010. *Modeling climate change impact on the hydrology of the Eastern Himalayas*. Technical Report 4. Kathmandu: ICIMOD. 12 pp.

Gupta, R.P.; Haritashya, U.K.; Singh P. 2005. Mapping dry/wet snow cover in the Indian Himalayas using IRS multispectral imagery. *Remote Sensing Environment* 97: 458-469.

Gurung, D.R.; Giriraj, A.; Aung, K.S.; Shrestha, B.; Kulkarni, A.V. 2011. *Snow-cover mapping and monitoring in the Hindu Kush-Himalayas*. Kathmandu: ICIMOD. 44 pp.

Hagg, W.; Braun, L.N. 2006. The influence of glacier retreat on water yield from high mountain areas: Comparison of Alps and Central Asia. In: *Climate and hydrology of mountain areas*, eds., de Jong, C.; Collins, D.; Ranzi, R. Chichester, UK: John Wiley & Sons. pp. 263-275.

Hagg, W.; Braun, L.N.; Kuhn, M.; Nesgaard, T.I. 2007. Modelling of hydrological response to climate change in glacierized Central Asian catchments. *Journal of Hydrology* 332: 40-53.

Hagg, W.; Hoelzle, M.; Wagner, S.; Klose, Z. 2011. Estimation of future glaciation and runoff in the Tanimas basin, Eastern Pamirs. *Hydrology and Earth System Sciences Discussions* 8: 1507-1540.

Hagg, W.; Hoelzle, M.; Wagner, S.; Mayre, E.; Klose, Z. 2013. Glacier and runoff changes in the Rukhk catchment, upper Amu-Darya basin until 2050. *Global and Planetary Change* http://dx.doi.org/10.1016/j.gloplacha.2013.05.005

Hagg, W.; Mayer, C.; Lambrecht, A.; Helm, A. 2008. Sub-debris melt rates on southern Inylchek Glacier, central Tian Shan. *Geografiska Annaler* 90 A(1): 55-63.

Hambrey, M.; Alean, J. 2004. *Glaciers*. Cambridge University Press. 376 pp.

Hannah, D.M.; Kansakar, S.L.; Gerrard, A.J.; Rees, G. 2005. Flow regimes of Himalayan rivers of Nepal: Nature and spatial patterns. *Journal of Hydrology* 308: 18-32.

Hasnain, S.I. 2009. Climate change: The tragedy of the Himalayas. *Time*. December 14, 2009.

Hasnain, S.I.; Thayyen, R.J. 1999. Controls on the major-ion chemistry of the Dokraini glacier meltwaters, Ganga Basin, Garhwal Himalaya, India. *Journal of Glaciology* 45(149): 87-92.

Hewitt, K. 2005. The Karakoram anomaly? Glacier expansion and the 'elevation effect,' Karakoram Himalaya. *Mountain Research and Development* 25: 332-340.

Hewitt, K.; Wake, C.P.; Young, G.J.; David, C. 1989. Hydrological investigations at Biafo Glacier, Karakorum Range, Himalaya; An important source of water for the Indus River. *Annals of Glaciology* 13: 103-108.

Hock, R. 2003. Temperature index melt modelling in mountain areas. *Journal of Hydrology* 282 (1-4): 104-115.

Hock, R.; Jansson, P.; Braun, L.N. 2005. Modelling the response of mountain glacier discharge to climate warming. In: *Global change and mountain regions: A state of knowledge overview*, eds., Huber, U.M.; Bugmann, H.K.M.; Reasoner, M.A. Dordrecht: Springer. pp. 243-252.

ICIMOD (International Centre for Integrated Mountain Development**).** 2007. *Inventory of glaciers, glacial lakes and identification of potential glacial lake outburst floods*. Kathmandu: ICIMOD. digital media.

Immerzeel, W.W.; Droogers, P.; de Jong, S.M.; Bierkens, M.F.P. 2009. Large-scale monitoring of snow cover and runoff simulation in Himalayan river basins using remote sensing. *Remote Sensing of Environment* 113: 40-49.

Immerzeel, W.W.; Pellicciotti, F.; Shrestha, A.B. 2012. Glaciers as a proxy to quantify the spatial distribution of precipitation in the Hunza Basin. *Mountain Research and Development* 32(1): 30-38.

Immerzeel, W.W.; van Beek, L.P.H.; Bierkens, M.F.P. 2010. Climate change will affect the Asian water towers. *Science* 328: 1382-1385.

IPCC (Intergovernmental Panel on Climate Change). 2001. *The scientific basis*. Contribution of Working Groups I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press. 881 pp.

IPCC. 2010. *IPCC statement on the melting of Himalayan glaciers*. Geneva, Switzerland. Available at http://www.ipcc.ch/pdf/presentations/himalaya-statement-20january2010.pdf (accessed on October 31, 2011).

Irvine-Fynn, T.D.L.; Hanna, E.; Barrand, N.E.; Porter, P.R.; Kohler, J.; Hodson, A.J. 2012. Examination of a physically based, high-resolution, distributed Arctic temperature-index melt model, on Midtre Lovénbreen, Svalbard. *Hydrological Processes*. DOI: 10.1002/hyp.9526.

Jansson, P.; Hock, R.; Schneider, T. 2003. The concept of glacier storage: A review. *Journal of Hydrology* 282: 116-129.

Jost, G.; Moore, R.D.; Menounos, B.; Wheate, R. 2012. Quantifying the contribution of glacier runoff to streamflow in the upper Columbia River Basin, Canada, *Hydrology and Earth System Sciences* 16: 849-860.

Jowit, J. 2008. *Melting glaciers start countdown to climate chaos*. The Observer. March 16, 2008. Available at http://www.guardian.co.uk/environment/2008/mar/16/glaciers.climatechange (accessed on October 30, 2011).

Kamalov, B.A. 1974. Sovremennoe oledenenie i stok v basseine Syr Darii (Glacier system and runoff in the Syr Darya basin at present). Tashkent: Central Asian Hydrometeorological Institute. *Trudi SARNIGMI* 12 (93): 79-81 (in Russian).

Kang, E.; Liu, C.; Xie, Z.; Shen, Y. 2009. Assessment of glacier water resources based on the glacier inventory of China. *Annals of Glaciology* 50(53): 204-210.

Kaser, G.; Fountain, A.; Jansson, P. 2003. *A manual for monitoring the mass balance of mountain glaciers*. IHP-VI. Technical Documents in Hydrology, No. 59. Paris: UNESCO. 137 pp.

Kaser, G.; Großhauser, M.; Marzeion, B. 2010. Contribution potential of glaciers to water availability in different climate regimes. *Proceedings of the National Academy of Sciences* 107(47): 20223-20227.

Kayastha, R.B.; Ageta, Y.; Nakawo, M. 2000a. Positive degree-day factors for ablation on glaciers in the Nepal Himalaya: Case study on Glacier AX010 in Shorong Himal, Nepal. *Bulletin of Glaciological Research* 17: 1-10.

Kayastha, R.B.; Ageta, Y.; Fujita, K. 2005. Use of positive degree-day method for calculating snow and ice melting and discharge in glacierized basins in the Langtang Valley, Central Nepal. In: *Climate and hydrology in mountain areas*, eds., De Jong, C.; Collins, D.; Ranzi, R. Chichester: John Wiley and Sons. pp. 47-59.

Kayastha, R.B.; Takeuchi, Y.; Nakawo, M.; Ageta, Y. 2000b. Practical prediction of ice melting beneath various thickness of debris cover on Khumbu Glacier, Nepal, using a positive degree-day factor. *IAHS publications* 264: 71-84.

Kayastha, R.B.; Ageta, Y.; Nakawo, M.; Fujita, K.; Sakai, A.; Matsuda, Y. 2003. Positive degree-day factors for ice ablation on four glaciers in the Nepalese Himalaya and Qinghai-Tibetan Plateau. *Bulletin of Glaciological Research* 20: 7-14.

Kemmerikh, A.O. 1972. Rol lednikov v stoke rek Sredney Asii (Glaciers' part in the stream flow in Central Asia). *Data of Glaciological Studies* 20: 82-94 (in Russian).

Kong, Y.; Pang, Z. 2012. Evaluating the sensitivity of glacier rivers to climate change based on hydrograph separation of discharge. *Journal of Hydrology* 434–435: 121–129.

Konovalov, V.G. 1985. Tayanie i stok s lednikov v basseinax rek Sredney Azii (Melt and runoff from glaciers in the river basins in Central Asia). Leningrad, USSR: Hydrometeoizdat. 235 pp. (in Russian).

Konovalov, V.G. 1997. The hydrological regime of Pamir–Alai glaciers. *Zeitschrift fuer Gletscherkunde und Glazialgeologie* 33(2): 125-131.

Konovalov, V.G. 2000. Computations of melting under moraine as a part of regional modeling of glacier runoff. *IAHS publications* 264: 109-118.

Konz, M.; Devkota, L. 2009. Manual on snow and glacier runoff modeling in the Himalayas. Consultancy Report. Kathmandu, Nepal: ICIMOD. 48 pp.

Konz, M.; Uhlenbrook, S.; Braun, L.; Shrestha, A.; Demuth, S. 2007. Implementation of a process-based catchment model in a poorly gauged, highly glacierized Himalayan headwater. *Hydrology and Earth System Sciences Discussions* 11: 1323-1339.

Kotlyakov, V.M. (Ed.). 1997. Atlas snego-ledovix zapasov mira (Atlas of Snow and Ice Resources of the World). Moscow, Russia: Academy of Sciences (in Russian). 512 pp.

Kotlyakov, V.M.; Lebedeva, I.M. 1999. Vozmozhnie izmeneniya abliatsii lednikov I lednikovogo stoka visochaishih gornih stran Azii v sviazi s globalnim potepleniem klimata. (Potential changes of ablation and glacier runoff in the High Asia due to global warming). *Data of Glaciological Studies* 88: 3-15 (In Russian).

Krenke, A.N. 1980. Lednikoviy stok v reki Sredney Azii i vozmozhnosti ego uregulirovaniya (Glacier runoff in Central Asian rivers and the options for its regulation). *Vodnie resursi (Water Resources)* 3: 5-19. (In Russian)

Krenke, A.N. 1982. Massoobmen v lednikovix sistemax na territorii SSSR (Mass exchange in glacier systems in the USSR). Leningrad: Hydrometeoizdat, 188 pp. (in Russian).

Krishna, A.P. 1996. Satellite remote sensing applications for snow cover characterization in the morphogenetic regions of upper Tista river basin, Sikkim Himalaya. *International Journal of Remote Sensing* 17(4): 651-656.

Krishna, A.P. 2005. Snow and glacier cover assessment in the high mountains of Sikkim Himalaya. *Hydrological Processes* 19: 2375-2383.

Kumar, A. 2011. Seasonal snow. In: *Encyclopedia of snow, ice and glacie*rs, eds., Singh, V.P.; Singh, P.; Harytashya, U.K. Netherlands: Springer. pp. 974-975.

Kumar, K.; Miral, M.S.; Joshi, V.; Panda, Y.S. 2002. Discharge and suspended sediment in the melt water of Gangotri Glacier, Garhwal Himalaya, India. *Hydrological Sciences Journal* 47(4): 611-619.

Kumar, V.; Singh, P.; Singh, V. 2010. Snow and glacier melt contribution in the Beas River at Pandoh Dam, Himachal Pradesh, India. *Hydrological Sciences Journal* 52(2): 376-388.

Kundzewicz, Z.W.; Mata, L.J.; Arnell, N.W.; Döll, P.; Jimenez, B.; Miller, K.; Oki, T.; Sen, Z.; Shiklomanov, I.A. 2008. The implications of projected climate change for freshwater resources and their management. *Hydrological Sciences Journal* 53: 3-10.

Kustas, W.P.; Rango, A.; Uijlenhoet, R. 1994. A simple energy budget algorithm for the snowmelt runoff model. *Water Resources Research* 30(5): 1515-1527.

Kuzmichenok, V.A. 2009. Monitoring of water, snow and glacial resources of Kyrgyzstan. In: *Assessment of snow, glacier and water resources in Central Asia*, eds., Braun, L.N.; Hagg, W.; Severskiy, I.V.; Young, G. IHP-HWRP, 8. pp. 84-98.

L'vovich, M.I. 1938. Opit classifikatsii rek SSSR (Classification of the rivers of USSR). *Trudi Gosudarstvennogo Gidrologicheskoko Instituta* 6: 79 (in Russian).

Lamadrid, A.J.; MacClune, K. 2010. *Climate and hydrological modeling in Hindu Kush-Himalaya Region*. Kathmandu, Nepal: ICIMOD, 75 pp.

Lebedeva, I.M. 1997. Changes in glacier runoff of the Hindu Kush rivers under global warming. *Data of Glaciological Studies* 83: 65-72 (in Russian).

Liu, Y.; Fukushima, Y.; Hiyama, T. 1999. Hydrological response of meltwater from glacier-covered mountain basin to climate change in northwest China. *IAHS publications* 256: 193-207.

Majeed, A.; Hussain, T.; Asghar, M.R. 2009. Long and medium range forecast for inflow at Tarbela. *Pakistan Journal of Meteorology* 5(10): 37-52.

Malone, E.L. 2010: *Changing glaciers and hydrology in Asia: Addressing vulnerabilities to glacier melt impacts*. Technical Report to USAID. Washington, DC, USA: USAID. 119 pp.

Mamatkanov, D.L.; Bazhanova, L.V.; Romanovskiy, V.V. 2006 Vodnie resursi Kyrgyzstana na sovremennom etape (Water resources of Kyrgyzstan at present). Bishkek: Ilim. 265 pp. (In Russian).

Martinec, J. 1989. Hour-to-hour snowmelt rates and lysimeter outflow during an entire ablation period. Snow cover and glacier variation. *IAHS Publications* 193: 19-28.

Mattson, L.E. 2000. The influence of a debris cover on the mid-summer discharge of Dom glacier, Canadian Rocky Mountains. *IAHS publications* 264: 25-33.

Mayer, C.; Lambrecht, A.; Belo, M.; Smiraglia, C.; Diolaiuti, G. 2006. Glaciological characteristics of the ablation zone of Baltoro glacier, Karakoram. *Annals of Glaciology* 43(1): 123-131.

Mihalcea, C.; Mayer, C.; Diolaiuti, G.; Lambrecht, A.; Smiraglia, C.; Tartar, G. 2006. Ice ablation and meteorological conditions on the debris-covered area of Baltoro glacier, Karakoram, Pakistan. *Annals of Glaciology* 43(1): 292-309.

Mool, P.K.; Bajracharya, S.R.; Shrestha, B. 2005. *Inventory of glaciers, glacial lakes and glacial lake outburst floods (GLOFs) affected by global warming in the mountains of Himalayan Region: Indus Basin - Pakistan*. Kathmandu, Nepal: ICIMOD.

Mukhopadhyay, B.; Dutta, A. 2010. A stream water availability model of Upper Indus Basin based on a topologic model and global climatic datasets. *Water Resources Management* 24: 4403-4443.

Pellicciotti, F.; Buergi, C.; Immerzeel, W.W.; Konz, M.; Shrestha, A.B. 2012. Challenges and uncertainties in hydrological modeling of remote Hindu Kush–Karakoram–Himalayan (HKH) basins: Suggestions for calibration strategies. *Mountain Research and Development* 32(1): 39-50.

Pelto, M.S. 2000. Mass balance of adjacent debris-covered and clean glacier ice in the North Cascades, Washington. *IAHS publications* 264: 35-42.

Pithan, F. 2011. A model study of the energy and mass balance of Chhota Shigri glacier in the Western Himalaya, India. *The Criospheric Discussions* 5(1): 95-129.

Qiu, J. 2008. China: The third pole. *Nature* 454: 393-396.

Qiu, J. 2010. Measuring the meltdown. *Nature* 468: 141-142.

Qobilov, T.; Pertziger, F.I.; Vasilina, L.; Baumgartner, M.F. 2000. Operational technology for snow-cover mapping in the Central Asian Mountains using NOAA-AVHRR data. *IAHS Publications* 267: 76-80.

Raina, V.K. 2009. *Himalayan glaciers: A state-of-art review of glacial studies, glacial retreat and climate change*. MoEF Discussion Paper. New Delhi, India: Ministry of Environment and Forests. 34 pp.

Rana, B.; Nakawo, M. 1997. Application of a conceptual precipitation-runoff model (HYCY-MODEL) in a debris-covered glacierized basin in the Langtang Valley, Nepal Himalaya. *Annals of Glaciology* 25: 226-231.

Rathore, B.P.; Kulkarni, A.V.; Sheraisa, N.K. 2009. Understanding future changes in snow and glacier melt runoff due to global warming in Wangar Gad basin, India. *Current Science* 97(7): 1077-1081.

Ratsek, I.V. 1991. Fluctuations and evolution of glacier runoff in the Naryn basin. PhD thesis summary. Moscow: Russian Academy of Sciences. 20 pp. (in Russian).

Rees, G.; Collins, D.N. 2004. *Snow and glacier aspects of water resources management in the Himalayas*. Final Technical Report: Volume 2. An Assessment of the impacts of deglaciation on the water resources of the Himalaya. Wallingford, UK: Centre for Ecology and Hydrology, 56 pp.

Rees, G.; Collins, D.N. 2006. Regional differences in response of flow in glacier-fed Himalayan rivers to climatic warming. *Hydrological Process* 20: 2157-2169.

Rupper, S.; Roe, G. 2008. Glacier changes and regional climate: A mass and energy balance approach. *Journal of Climate* 21: 5384-5401.

Savoskul, O.S.; Shevnina, E. 2011. Simulating water availability in the Syr Darya Basin in 2070-99 under GFDL99 and HadCM3-based climate scenarios. Materials of the International Symposium on Changing Cryosphere, Water Availability and Sustainable Development in Central Asia. Urumqi, China: Chinese Academy of Sciences. p. 107.

Savoskul, O.S.; Shevnina, E.V.; Perziger, F.I. 2004. How much water will be available for irrigation in the future? The Syr Darya Basin. In: Aerts, J.C.J.H.; Droogers, P. (eds). *Climate change in contrasting river basins*. Wallingford, UK: CABI. pp. 93-113.

Savoskul, O.S.; Smakhtin, V. 2013. *Glacier systems and seasonal snow cover in six major Asian river basins: Water storage properties under changing climate*. Colombo, Sri Lanka: International Water Management Institute (IWMI). 69p. (IWMI Research Report 149).

Savoskul, O.S. (Ed.). 2003. *Water, climate, food and environment in the Syr Darya Basin*. Contribution to ADAPT project. Final Report. Tashkent: IWMI. 59 pp. Available at http://www.weap21.org/downloads/AdaptSyrDarya.pdf (accessed on March 31, 2011).

Scheglova, O.P. 1960. Pitanie rek Sredney Azii (Rivers' budget in Central Asia). Tashkent: University Press. 243 pp.

Schiermeier, Q. 2010. Glacier estimate is on thin ice. *Nature* 463: 276-277.

Sharma, S. 1999. Mass balance studies of Changme Khangpu glacier, Mangan District, Sikkim. Materials of the Symposium on Snow, Ice and Glaciers. India, New Delhi. pp. 10-11.

Shekhar, M.S.; Chand, H.; Kumar, S.; Srinivasan, K.; Ganju, A. 2010. Climate change studies in the western Himalaya. *Annals of Glaciology* 51(54): 105-112.

Shetinnikov, A.G. 1976. Ledniki basseina reki Pskem. (Glaciers in the Pskem river basin). Leningrad: Hydrometeoizdat. 120 pp. (in Russian).

Shetinnikov, A.G. 1998. Morfologiya i oledenenie Pamiro-Alaya. (Morphology and glacier systems of Pamir-Aay). Tashkent: SANIGMI. 219 pp. (in Russian).

Shults, V.L. 1965. Reki Sredney Asii (Rivers of Central Asia) Leningrad: Hydromeoizdat. 285 pp. (in Russian)

Singh, P.; Bengtsson, L. 2003. Effect of warmer climate on the depletion of snow-covered area in the Satluj basin in the western Himalayan region. *Hydrological Sciences Journal* 48(3): 413-425.

Singh, P.; Bengtsson, L. 2004. Hydrological sensitivity of a large Himalayan basin to climate change. *Hydrological Processes* 18: 2363-2385.

Singh, P.; Bengtsson, L. 2005. Impact of warmer climate on melt and evaporation for the rainfed, snowfed and glacierfed basins in the Himalayan region. *Journal of Hydrology* 300: 140-154.

Singh, P.; Bengtsson, L.; Berndtsson, R. 1995. Relating air temperature to the depletion of snow covered area in a Himalayan basin. *Nordic Hydrology* 34: 267-280.

Singh, P.; Haritashya, U.K.; Kumar, N. 2008. Modelling and estimation of different components of streamflow for Gangotri Glacier basin, Himalayas. *Hydrological Sciences Journal* 53(2): 309-322.

Singh, P.; Jain, S.K. 2002. Snow and glacier melt in the Satluj river at Bhakra Dam in the western Himalayan region. *Hydrological Sciences Journal* 47: 93-106.

Singh, P.; Jain, S.K. 2003. Modelling of streamflow and its components for a large Himalayan basin with predominant snowmelt yields. *Hydrological Sciences Journal* 48(2): 257-275.

Singh, P.; Jain, S.K.; Kumar, N. 1997. Snow and glacier melt runoff contribution in the Chenab River at Akhnoor. *Mountain Research and Development* 17(1): 49-56.

Singh, P.; Kumar, N. 1996. Determination of snowmelt factor in the Himalayan region. *Hydrological Sciences Journal* 41(3): 301-310.

Singh, P.; Singh, V.P. 2001. Snow and glacier hydrology. Netherlands: Kluwer Academic Publishers. 678 pp.

Sokalskaya, A.M. 1994. Formation of glacier runoff in Tien Shan. PhD thesis summary. Moscow: Russian Academy of Sciences. 26 pp. (in Russian).

Sorg, A.; Bolch, T.; Stoffel, M.; Solomina, O.; Beniston, M.; 2012. Climate change impacts on glaciers and runoff in Tien Shan (Central Asia). *Nature Climate Change* 2: 725-731.

Swaroop, S.; Shukla, S.P.; Oberoi, L.K.; Siddique, M.A.; Bejarniya, B.R. 2001. Short-term runoff and ablation characteristics of Triloknath Glacier, Lahaul and Spiti District, Himachal Pradesh. *Geological Survey of India, Special Publication* 53: 91-96.

Tahir, A.A.; Chevallier, P.; Arnaud, Y.; Ahmad, B. 2011. Snow cover dynamics and hydrological regime of the Hunza River basin, Karakoram Range, Northern Pakistan Hydrologic. *Earth System Sciences Discussions* 8: 2821-2860.

Tangborn, W.; Rana, B. 2000. Mass balance and runoff of the partially debris-covered Langtang Glacier, Nepal. *IAHS publications* 264: 53-61.

Thayyen, R.J.; Gergan, J.T. 2010. Role of glaciers in watershed hydrology: a preliminary study of a “Himalayan catchment”. *The Cryosphere* 4: 115-128.

Thayyen, R.J.; Gergan, J.T.; Dobhal, D.P. 2007. Role of glaciers and snow cover on headwater river hydrology in monsoon regime – Micro-scale study of Din Gad catchment, Garhwal Himalaya, India. *Current Science* 92(3): 376-382.

UNEP (United Nations Environment Programme). 2009. *Recent trends in melting glaciers, tropospheric temperatures over the Himalayas and summer monsoon rainfall over India*. Kenya, Nairobi: UNEP. 45 pp.

Vilesov, E.N. 1999. Izmeneniya lednikovogo stoka v usloviyah degradatsii oledeneniya. (Changes of glacier runoff in the recessing glacier systems). *Data of Glaciological Studies* 87: 78-83 (in Russian).

Viviroli, D.; Archer, D.R.; Buytaert, W. 2011. Climate change and mountain water resources: Overview and recommendations for research, management and policy. *Hydrology and Earth System Sciences* 15: 471-504.

Wagnon, P.; Linda, A.; Arnaud, Y.; Kumar, R.; Sharma, P.; Vincent, C.; Pottakkal, J.G.; Berthier, E.; Ramanathan, A.; Hasnain, S.I.; Chevallier, P. 2007. Four years of mass balance on Chhota Shigri Glacier, Himachal Pradesh, India, a new benchmark glacier in the western Himalaya. *Journal of Glaciology* 53(183): 603-611.

WGMS (World Glacier Monitoring Service). 1991. *Glacier Mass Balance Bulletin. Bulletin No. 1 (1988-1989)*, eds., Haeberli, W.; Herren, E. IAHS (ICSI)-UNEP-UNESCO. Zurich, Switzerland: World Glacier Monitoring Service.

WGMS. 1993. *Glacier Mass Balance Bulletin. Bulletin No. 2 (1990-1991)*, eds., Haeberli, W.; Herren, E.; Hoelzle, M. IAHS (ICSI)-UNEP-UNESCO. Zurich, Switzerland: World Glacier Monitoring Service.

WGMS. 1994. *Glacier Mass Balance Bulletin. Bulletin No. 3 (1992-1993)*, eds., Haeberli, W.; Herren, E.; Bosch, H. IAHS (ICSI)-UNEP-UNESCO. Zurich, Switzerland: World Glacier Monitoring Service.

WGMS. 1996. *Glacier Mass Balance Bulletin. Bulletin No. 4 (1994-1995)*, eds., Haeberli, W.; Hoelzle, M.; Suter, S. IAHS (ICSI)-UNEP-UNESCO. Zurich, Switzerland: World Glacier Monitoring Service.

WGMS. 1999. *Glacier Mass Balance Bulletin. Bulletin No. 5 (1996-1997)*, eds., Haeberli, W.; Hoelzle, M.; Frauenfelder, R. IAHS (ICSI)-UNEP-UNESCO. Zurich, Switzerland: World Glacier Monitoring Service.

WGMS. 2001. *Glacier Mass Balance Bulletin. Bulletin No. 6 (1998-1999)*, eds., Haeberli, W.; Frauenfelder, R.; Hoelzle, M. IAHS (ICSI)-UNEP-UNESCO-WMO. Zurich, Switzerland: World Glacier Monitoring Service.

WGMS. 2003. *Glacier Mass Balance Bulletin. Bulletin No. 7 (2000-2001)*, eds., Haeberli, W.; Frauenfelder, R.; Hoelzle, M.; Zemp, M. IAHS (ICSI)-UNEP-UNESCO-WMO. Zurich, Switzerland: World Glacier Monitoring Service.

WGMS. 2005. *Glacier Mass Balance Bulletin. Bulletin No. 8 (2002-2003)*, eds., Haeberli, W.; Noetzli, J.; Zemp, M.; Baumann, S.; Frauenfelder, R.; Hoelzle, M. IUGG (CCS)-UNEP-UNESCO-WMO. Zurich, Switzerland: World Glacier Monitoring Service.

WGMS. 2007. *Glacier Mass Balance Bulletin. Bulletin No. 9 (2004-2005)*, eds., Haeberli, W.; Hoelzle, M.; Zemp, M. ICSU (FAGS)-IUGG (CCS)-UNEP-UNESCO-WMO. Zurich, Switzerland: World Glacier Monitoring Service.

WGMS. 2009. *Glacier Mass Balance Bulletin. Bulletin No. 10 (2006-2007)*, eds., Haeberli, W.; Gärtner-Roer I.; Hoelzle, M.; Paul F.; Zemp, M. ICSU (WDS)-IUGG (IACS)-UNEP-UNESCO-WMO. Zurich, Switzerland: World Glacier Monitoring Service.

WGMS. 2011. *Glacier Mass Balance Bulletin. Bulletin No. 11 (2008-2009)*, eds., Zemp, M.; Nussbaumer, S.U.; Gärtner-Roer, I.; Hoelzle, M.; Paul, F.; Haeberli, W. ICSU (FAGS)-IUGG (IACS)-UNEP-UNESCO-WMO. Zurich, Switzerland: World Glacier Monitoring Service.

WGMS; NSIDC (National Snow and Ice Data Center). 2009. (updated version: 2012) *World Glacier Inventory*. Zurich, Switzerland: WGMS. Boulder, USA: NSIDC. Available at http://nsidc.org/data/glacier_inventory/ (accessed on March 9, 2011).

Willmott, C.J.; Matsuura, K. 2006. On the use of dimensioned measures of error to evaluate the performance of spatial interpolators. *International Journal of Geographical Information Science* 20(1): 89-102.

Willmott, C.J.; Rowe, C.M.; Mintz, Y. 1985. Climatology of the terrestrial seasonal water cycle. *Journal of Climatology* 5: 589-606.

Winiger, M.; Gumpert, M.; Yamout, H. 2005. Karakoram–Hindukush–Western Himalaya: assessing high-altitude water resources. *Hydrological Processes* 19: 2329-2338.

Xie, Z.-C.; Wang, X.; Qing-Hua, F.; Ersi, K.; Chao-Hai, L.; Qiao-Yuan, L. 2006. Modeling the response of glacier systems to climate warming in China. *Annals of Glaciology* 43(1): 313-316.

Xu, J.; Shrestha, A.; Vaidya, R.; Eriksson, M.; Hewitt, K. 2007. *The melting Himalayas: Regional challenges and local impacts of climate change on mountain ecosystems and livelihoods*. ICIMOD Technical Paper. Kathmandu: ICIMOD. 24 pp.

Yang, W.; Yao, T.D.; Xu, B.Q.; Wu, G.J.; Ma, L.L.; Xin, X.D. 2008. Quick ice mass loss and abrupt retreat of the maritime glaciers in the Kangri Karpo Mountains, southeast Tibetan Plateau. *Chinese Science Bulletin* 53(16): 2457-2551.

Yao, T.D.; Pu, J.; Lu, A.; Wang, Y.; Yu, W. 2007. Recent glacial retreat and its impact on hydrological processes on the Tibetan Plateau, China. Arctic. *Antarctic, Antarctic and Alpine Research* 39(4): 642-650.

Ye, B.; Ding, Y.; Liu, F.; Liu, C. 2003. Responses of various-sized alpine glaciers and runoff to climatic change. *Journal of Glaciology* 49(164): 1-8.

Young, G.J.; Hewitt, K. 1990. Hydrology research in the Upper Indus basin, Karakoram Himalaya, Pakistan. *IAHS Publications* 190: 139-152.

Young, G.J.; Hewitt, K. 1993. Glaciohydrological features of the Karakoram Himalaya: Measurements, possibilities and constraints. *IAHS Publications* 218: 273-283.

Zhang, Y.; Liu, S.; Ding, Y. 2006. Observed degree-day factors and their spatial variation on glaciers in western China. *Annals of Glaciology* 43: 301-306.

Zhang, Y.; Liu, S.; Xu, J.; Shangguan, D. 2007. Glacier change and glacier runoff variation in the Tuotuo River basin, the source region of Yangtze River in western China. *Environmental Geology* 56: 59-68.

Zhetker, M.I.; Tsarev, B.K. 1991. Gliatsiologiya gornix oblastey: snezhniy pokrov, ledniki, lavini (Glaciology of the mountain regions: snow cover, glaciers, snow avalanches). *Trudi SARNIGMI* 140. Tashkent, USSR: Central Asian Hydrometeorological Institute. 134 pp. (in Russian)

IWMI Research Reports

150 *Glacier Systems and Seasonal Snow Cover in Six Major Asian River Basins: Hydrological Role under Changing Climate*. Oxana S. Savoskul and Vladimir Smakhtin. 2013.

149 *Glacier Systems and Seasonal Snow Cover in Six Major Asian River Basins: Water Storage Properties under Changing Climate*. Oxana S. Savoskul and Vladimir Smakhtin. 2013.

148 *Evaluating the Flow Regulating Functions of Natural Ecosystems in the Zambezi River Basin*. Matthew McCartney, Xueliang Cai and Vladimir Smakhtin. 2013.

147 *Urban Wastewater and Agricultural Reuse Challenges in India*. Priyanie Amerasinghe, Rajendra Mohan Bhardwaj, Christopher Scott, Kiran Jella and Fiona Marshall. 2013.

146 *The Water Resource Implications of Changing Climate in the Volta River Basin.* Matthew McCartney, Gerald Forkuor, Aditya Sood, Barnabas Amisigo, Fred Hattermann and Lal Muthuwatta. 2012.

145 *Water Productivity in Context: The Experiences of Taiwan and the Philippines over the Past Half-century*. Randolph Barker and Gilbert Levine. 2012.

144 *Revisiting Dominant Notions: A Review of Costs, Performance and Institutions of Small Reservoirs in Sub-Saharan Africa.* Jean-Philippe Venot, Charlotte de Fraiture and Ernest Nti Acheampong. 2012.

143 *Smallholder Shallow Groundwater Irrigation Development in the Upper East Region of Ghana.* Regassa E Namara, J.A. Awuni, Boubacar Barry, Mark Giordano, Lesley Hope, Eric S. Owusu and Gerald Forkuor. 2011.

142 *The Impact of Water Infrastructure and Climate Change on the Hydrology of the Upper Ganges River Basin*. Luna Bharati, Guillaume Lacombe, Pabitra Gurung, Priyantha Jayakody, Chu Thai Hoanh and Vladimir Smakhtin. 2011.

141 *Low-cost Options for Reducing Consumer Health Risks from Farm to Fork Where Crops are Irrigated with Polluted Water in West Africa.* Philip Amoah, Bernard Keraita, Maxwell Akple, Pay Drechsel, R.C. Abaidoo and F. Konradsen. 2011.

140 *An Assessment of Crop Water Productivity in the Indus and Ganges River Basins: Current Status and Scope for Improvement*. Xueliang Cai, Bharat R. Sharma, Mir Abdul Matin, Devesh Sharma and Sarath Gunasinghe. 2010.

Electronic copies of IWMI's publications are available for free.

Visit

www.iwmi.org/publications/index.aspx

Postal Address
P O Box 2075
Colombo
Sri Lanka

Location
127 Sunil Mawatha
Pelawatta
Battaramulla
Sri Lanka

Telephone
+94-11-2880000

Fax
+94-11-2786854

E-mail
iwmi@cgiar.org

Website
www.iwmi.org

IWMI International Water Management Institute

IWMI is a member of the CGIAR Consortium and leads the:

CGIAR

RESEARCH PROGRAM ON
Water, Land and Ecosystems

ISSN: 1026-0862
ISBN: 978-92-9090-769-5