Brief for GSDR 2015

Hydrological modelling and their biases: constraints in policy making and sustainable water resources development under changing climate in the Hindukush-Karakoram-Himalayas

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The Hindukush-Karakoram-Himalayan (HKH) mountain ranges and highlands of the Tibetan Plateau (TP) contain large mountain glaciers of the world, and nourishes large Asian river basins with significant amounts of snow and glacier melt, thus are susceptible to global warming and climate change. Therefore, precise and accurate policy making and sustainable water resource development are vital to cater for needs of food and power generation of billions of people. Precise and accurate policy making and sustainable water resources development are dependent on the accuracy of hydrological modelling and its future forecasts, though contain inevitable significant uncertainties. Current study discusses hydrological modelling uncertainties, biases and their causes in the Upper Indus Basin (UIB), which is originating from the HKH-TP region (see Figure 1a-c).

The UIB receives winter precipitation from westerlies, whereas summer precipitation is caused by monsoon depressions (see Figure 1a). Most of the UIB (70-80% of the entire basin) remains covered by winter snowfall, although snow-glacier cover reaches to 9-11% of the basin area during summer months (Hewitt 2005,2013; Khan et al., 2014a). River flows from the UIB cater for agricultural and power production needs of millions of people, thus play vital role in agro-economic growth of Pakistan. Snow and glacier melt contribute about 50-80% of annual flows in all sub-basins of the UIB, though various studies show significant variability and uncertainty in snow and glacier melt contribution to annual river flows (see Table 1). For example the variability of glacier-melt for the UIB at Besham Qila ranges between ~20% to 68% of the annual flows, and for the Astore sub-basin is ~18% to 63% of the annual flows (Table 1). Such variability and uncertainties restrict precise and accurate policy making and sustainable water resources development, in the UIB. Slight variability among various studies (Table 1) can be due to difference in time periods, use of different snow-glacier areas and use of different methods. However significant variability and uncertainties are caused by three main reasons: 1) use of an overestimated drainage basin areas, 2) use of underestimated precipitation, and 3) use of biased calibration methods. These are discussed as follows.

1) Use of overestimated basin areas

One of the main cause of hydrological modelling uncertainties is the use of an overestimation of the UIB drainage area. The drainage area of the UIB at Besham Qila flow gauging station (see Figure 1b) is ~162000 km^2 to ~265000 km^2 based on various published studies

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(see details in Khan et al., 2014b). The precise and accurate drainage area of the UIB at Besham Qila is ~165000 km^2, whereas overestimation was caused by including the endorheic areas as part of the UIB (Khan et al., 2014b; Reggianni and Rientjes, 2014; Yu et al., 2013). Hydrological modelling studies (Table 1) based on overestimated drainage basin areas (such as Immerzeel et al., 2009; Bookhagen and Burbank, 2010; Lutz et al., 2014a,b) may contain significant uncertainties and biases and need to be revisited. Thus, such studies' future forecasts are biased and cannot be used in precise and accurate policy making and sustainable water resource development.

2) Use of underestimated precipitation

An underestimated precipitation can produce significant hydrological modelling calibration artefacts, and thus result in an overestimated glacier-melt, hence produces bias in future forecasts (Schaefeli et al., 2005). Due to ease in access and availability of gridded precipitation datasets, hydrological modelling studies (such as Immerzeel et al., 2009, 2010, 2013;Lutz et al., 2014a;Tahir et al., 2011) used various gridded precipitation datasets in their modelling. Unfortunately, due attention has not been paid to the accuracy of adopted gridded precipitation datasets. The datasets used in various hydrological modelling studies reveal that in almost all studies average basin precipitation is significantly less than the measured and or modelled flow (Table 2). Table 2 shows that in almost all studies precipitation data used are equivalent to ~20-50% of measured flow. In addition, glacier mass balance studies reveal that glacier mass imbalance flow contribution ranges between 4% to 8% of total annual flows at Besham Qila (for the entire UIB, for other sub-basins see referenced studies), although actual flow contribution will be far less than the quoted percentages due to unaccounted evapo-transpiration, sublimation, glacial lake interception losses (Gardner et al., 2013; Kaab et al., 2012, 2014). It should be noted that in Table 2 mass imbalance (precipitation minus flows) does not include evapo-transpiration, sublimation, ground water storage change, glacier positive mass balance interception, glacial lake interception and other such losses, although these losses could form significant part of the mass balance. Besides ignoring significant amount of losses, two widely used gridded precipitation datasets at 0.25^o grid resolution: Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation of Water Resources, APHRODITE (Yatagai et al., 2009, 2012), and Tropical Rainfall Measuring Mission, TRMM (Huffman et al., 2007, 2014), significantly underestimate precipitation for all sub-basins, though other gridded datasets also underestimate precipitation. It should be noted that in some studies precipitation and flows seem balance, and is due to overestimated drainage basin areas, due to which specific runoff (runoff/drainage area) is negatively biased. Interestingly, APHRODITE and TRMM datasets overestimate precipitation in the TP region (Yin et al., 2008; Prakash et al., 2013; Andermann et al., 2011; Palazzi et al., 2013). The datasets used in various studies are mainly based on precipitation data from climatic stations located at low altitudes in the UIB valleys, and are not true representative of high altitudes' precipitation (Hewitt 2005, 2013; Winiger et al., 2005), and is a main reason of gridded datasets' precipitation underestimation. It is noteworthy that there are more climatic stations in the eastern Himalayas as compared to the UIB (Yatagai et al., 2009, 2012). Therefore the accuracy of precipitation datasets could be much better in the eastern Himalayas as compared to the UIB. The reported glacier melt annual flow contribution in the eastern Himalayas is far less than in the sub-basins of the UIB (Lutz et al., 2014a), besides greater percentage snow-glacier area as compared total basin areas (such as Koshi in the eastern Himalayan sub-basin and Astore, Gilgit in the UIB, see Table 1). Thus, almost all current available hydrological modelling studies for the UIB are based on underestimated precipitation data, hence their current snow, glacier melt estimates and future forecasts are significantly bias, and therefore cannot be used for precise and accurate water resource planning and management.

3) Use of bias calibration methods

As most of the hydrological modelling studies are based on underestimated precipitation datasets, therefore bias calibration methods have been adopted for measured and modelled flow calibration. Almost all the available hydrological modelling studies are based on temperature melt models (such as Snow melt Runoff Model; SRM), therefore their calibration were significantly dependent on melt rates from snow and ice. The snow and ice melt rates in the UIB are ~4mm/°C/day for snow and ~7 mm/°C/day for clean ice (Singh et al., 2000; Zhang et al., 2006). Khan et al. (2014a) have shown that ice ranges between ~12% to 38% of total snow and ice during ablation period. This study also noticed that most of the ice was below 5000m in all sub-basins. However, Tahir et al. (2011) adopted low melt rates for lower altitudes and higher melt rates (~7 mm/°C/day for ice) for higher altitudes (above 5500m), during summer months, and could be due to use of underestimated precipitation. In addition, the snowmelt and rain runoff coefficients adopted are ~0.15 to 0.2, which means ~80 to 85% snowmelt and rain runoff has been accounted for losses. Thus, their future forecasts were not significantly susceptible to any snow-glacier cover shrinkage or change in precipitation. Similarly, other hydrological modelling studies (such as Immerzeel et al., 2009,2010, 2013; Bookhagen and Burbank, 2010; Lutz et al., 2014a,b) have used ice melt rates for the entire snow-glacier areas during summer months, and thus overestimated snow-glacier melt. Interestingly, some hydrological models have not been calibrated for measured flows at all (such as in Bookhagen and Burbank, 2010; Immerzeel et al., 2013). In these studies calibration parameters of sub-basins in the eastern Himalayas have been adopted, that is why the modelled flow for the entire UIB in Bookhagen and Burbank (2010) is almost twice of the measured flow (4200 m^3/s > ~2400 m^3/s), whereas in Immerzeel et al. (2013) flow is far less than the measured flow at Shigar gauging station (602 mm/yr < 963mm/yr), although this study is for a tributary of the whole basin. However, both these studies suggest that calibration parameters from the eastern Himalayan sub-basins can produce significant biases. Another surprising example of hydrological modelling can be seen in Immerzeel et al. (2009,2010), where model has been calibrated for the UIB, with two different drainage basin areas, but the measured and modelled flows calibration is the same (for comparison see Figure 7 in Immerzeel et al., 2009 and supplementary Figure S1 in Immerzeel et al., 2010). Such comparison shows that due importance has not been given to modelling and calibration in these two studies, at least. Another important calibration parameter in the temperature based melt modelling is temperature lapse rates, as use of underestimated lapse rate can significantly overestimate melt and vice versa (Dey et al.,1989). Temperature lapse rates significantly varies during each month, and are different for each sub-basin of the UIB (Khan et al., 2014a), though in above mentioned studies a uniform lapse rates have been used. Thus, all above studies encountered by calibration errors, and their results and forecasts may contain significant biases.

In conclusion, all above mentioned hydrological modelling studies are biased due to use of either over estimated drainage areas, underestimated precipitation, calibration artefacts or a combination of some or all of these factors. Unfortunately, current available hydrological modelling studies contain significant variability, uncertainties and may contain large biases, and are not suitable for precise and accurate policy making and sustainable water resources development, hence need to be revisited. Therefore, there is an intense need to improve hydrological modelling in the UIB and to provide precise and accurate future water resources forecasts under changing climate, and to enable policy makers and water resources managers to accurately plan and manage future water resources. All above also cautions to avoid use of overestimated drainage basin areas, underestimated precipitation datasets without prior bias correction and to use best available calibration methods in future hydrological modelling, at least in the UIB. Such studies are also recommended for other regions of the world, where snow and glacier melt constitute most of the river flows, particularly in the other sub-basins of the HKH-TP region.

Figure 1. a) Map showing location of the Upper Indus Basin (UIB) in the regional geography and climatic circulations. Climatic circulations have been adopted and re-developed from Yao et al. (2012), Bolch et al. (2012), and Hodges (2006). The best available drainage basin boundary of the UIB shown in sky blue color based on Khan et al. (2014b), whereas red polygon is an additional overestimated drainage area by other researchers, such as Immerzeel et al. (2009), Bookhagen and Burbank (2010), and Lutz et al. (2014a,b), while olive is an additional endorheic area included in the UIB by Mukhopadhyay (2012), b) Location of the UIB and Indus River, which takes start in the Tibetan Plateau near to Mansarovar lake. Figure also shows numerous peaks in the UIB, location of Besham Qila flow gauging station and Tarbela Dam, c) Sub-basins and river morphology in the study area. Note: SRTM DEM highest altitude is slightly lower than peak altitude of K2, and is due to well know layover and voids errors in the DEM (see for details Khan et al., 2014b; Mukhopadhyay 2012).

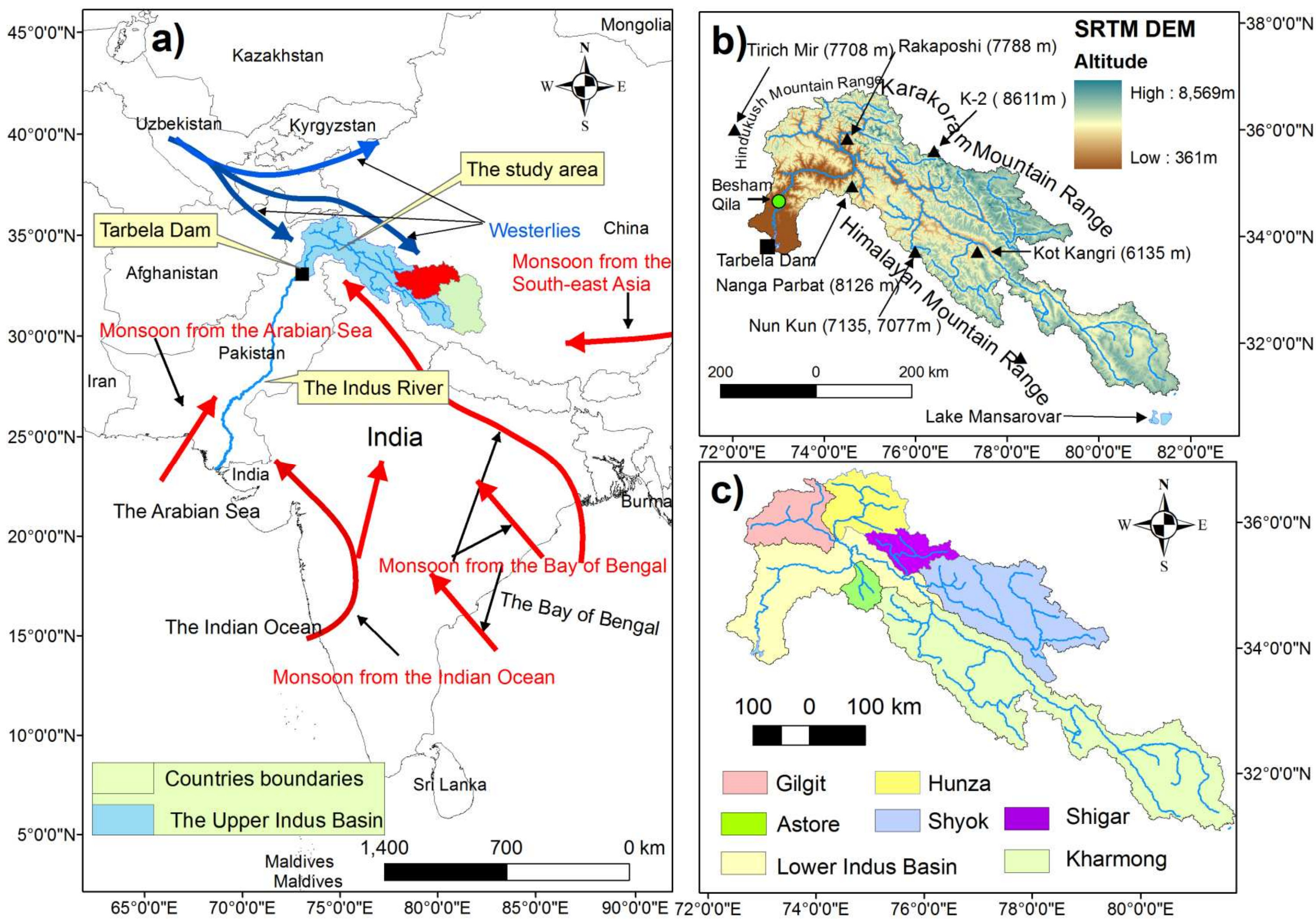

Table 1: Glacier-, snow-melt, rain runoff and base flow contributions to stream flows in various basins.

Basin	Station name	Glacierized area*	Data period	Glacier melt	Snow melt	Rain runoff and base flow	References**
			1974-2000	51		49	7
			1980-2010	24.5	43.5	32	1
Gilgit	Gilgit	836.3 (~6.6%)	1966-2010	23		77	2
			1998-2007	54.2	26	19.8	3
			1966-2010	31	43	26	1
			1974-2000	64		36	7
Hunza	Dainyur	3843 (~27.9%)	1966-2010	47		53	2
			1998-2007	80.6	9.6	9.8	3
			1971-2000	70.6	14.1	15.3	4
		2700 (~40.6%)	1985-1998	83.5		16.5	5
Shigar	Shigar		1985-1998	35	43	22	1
		2121 (~30.3%)	1985-1998	52.7		47.3	2
			1998-2007	83.5	6.9	9.6	3
			1973-2010	34	41	25	1
			1974-2000	54		46	7
Shyok	Yogo	7696 (~23.2%)	1973-2010	56.3		43.7	2
			1998-2007	80.4	9.7	9.9	3
Kharmong	Kharmong	2522 (~3.6%)	1982-2010	21.5	44.5	34	1
			1998-2007	54.6	27.6	17.8	2
			1974-2009	18	50	31	1
			1974-2000	63		37	7
Astore	Doyian	541 (~13.5%)	1974-2009	19		81	2
			1998-2007	46.4	36.7	16.9	3
			1970-2010	25.5	45.5	29	1
Shyok, Shigar, Kharmong	Kachura	12339 (~10.8%)	1974-2000	47		53	7
			1998-2007	72.7	15.1	12.2	3
			1971-2000	33.1	23.6	43.3	4
		……….	2001-2005	31.9	39.7	28.4	6
			1969-2010	24.3		75.7	2
The Upper Indus Basin	Besham		1969-2010	20.5	49.5	30	1
		18334 (~10.6%)	1998-2007	67.3	17.6	15.1	2
			1974-2000	48		52	7
			1971-2000	30.4	29.2	40.4	4
Dudh Koshi, Rabuwa Bazar	Koshi	510 (~14%)	1988-2006	7.4		92.6	8
			1998-2007	18.8	4.8	76.4	3

**References are: 1 is Mukhopadhyay and Khan (2014), 2 is Yu et al. (2013), 3 is Lutz et al. (2014a), 4 is Lutz et al. (2014b), 5 is Bocchiala et al. (2011), 6 is Immerzeel et al. (2009), 7 is Naz (2011), 8 is Racoviteanu et al. (2013). *Glacierized areas are based on RGI v 3.2 data (Pfeffer et al., 2014), except for Bocchiala et al. (2011). Areas are in km^2, while values in brackets are percent glacier area as compared to the total basin area in the respective basin. River flow components' separation in various studies is different in all studies, therefore in some rows few components are combined, and are in percent of the total annual flows. Flow component contributions for Lutz et al. (2014) and Naz (2011) are based on their published paper/thesis and additional results acquired from the authors.

Table 2: Comparison of mass imbalance between precipitation and gauge/modelled flow in various hydrological modelling studies, where different precipitation datasets and models have been used.

Basin	Drainage basin area	Study/flow data period	Precipitation	Measured flow	Modelled flow	Mass imbalance[a]	Mass imbalance[b]	Precipitation dataset used	References*
Gilgit	12671[c]	1980-2010	315	724	796	-56.5	-60.4	M and W data	1
	12800	1990-1996	162.5	728.8	632.4	-77.7	-74.3	Climatic stations data	2
	12671[c]	1998-2007	326	744	584.7	-67.4	-44.2	APHRODITE*1.17	3
Hunza	13733	1966-2010	229.7	731	735	-68.6	-68.7	M and W data	1
	13925	1990-1996	162.5	636.6	613.96	-74.5	-73.5	Climatic stations data	2
		2000-2004	176	674	694.2	-73.9	-74.6	APHRODITE	4
	13732[c]	1998-2007	205	612	1107.6	-72.3	-81.5	APHRODITE*1.17	3
		1971-2000	692	708	557	-2.3	24.2	Study Modelled	5
Shigar	6650	1985-1997	550	963	953	-42.9	-42.3	Study Modelled	6
		1985-1998	201.7	963	1332	-79.1	-84.9	M and W data	1
		1985-1998	~1100	963	602**	17.3	87.7	Study Modelled	7
		1985-1998	264	963	1764.3	-72.9	-85	APHRODITE*1.17	3
Shyok	140129	1973-2010	251.15	80.9	133.4	210.4	88.3	M and W data	1
	33157[c]	1998-2007	175.5	385	882.8	-54.4	-80.1	APHRODITE	3
Kharmong	72887	1973-2010	388	195.7	208.4	98.3	86.2	M and W data	1
	70030[c]	1998-2007	161	197.2	273.9	34.1	-41.2	APHRODITE*1.17	3
Astore	3750	1990-1996	496	1439	1280.8	-65.5	-61.3	Climatic stations data	2
	3899[c]	1998-2007	430.5	1106	574.3	-61.1	-25	APHRODITE*1.17	3
The Upper Indus Basin at Besham Qila	265598	1979-2010	315	320	268.6	-1.6	17.3	M and W data	1
	200677	2001-2005	311	367	360	-15.3	-13.6	TRMM 3B43	8
	162393	2001-2007	312	466	470.7	-33	-33.7	TRMM 3B43	9
	205536	1979-2010	300	414	658	-27.5	-54.4	TRMM 2B31	10
	200677	1998-2007	218.9	382	476	-42.7	-54	APHRODITE*1.17	3
	200677	1971-2000	671	379.8	291	76.7	130.6	Study Modelled	5

*References are: 1 is Mukhopadhyay 2012, 2 is Akhtar et al. (2008), 3 is Lutz et al. (2014a), 4 is Tahir et al. (2011), 5 is Lutz et al. (2014b), 6 is Bocchiala et al. (2011), 7 is Immerzeel et al. (2013), 8 is Immerzeel et al. (2009), 9 is Immerzeel et al. (2010), 10 is Bookhagen and Burbank (2010). Basin areas are in km^2 and as per corresponding studies. [c] Area values have been adopted from Khan et al. (2014), wherever in relevant study no record is provided. Mass imbalance[a] is percentage differences between measured flow and available/adopted precipitation data (i.e (Precipitation - Measured Flow)/Measured Flow *100)), while Mass imbalance[b] is percentage differences between modelled flow and available/adopted precipitation data (i.e (Precipitation - Modelled Flow)/Modelled Flow *100)). Negative mass balance means that measured/modelled flow is greater than precipitation, therefore glacier melt compensate the difference. Precipitation data is in mm/yr, and is based on respective datasets used in various studies. Gauging stations flow data is as per study periods in various studies, while for Mukhopadhyay (2012) values are based on the entire available datasets provided in Mukhopadhyay and Khan (2014). M and W data is Matsuura and Willmott (2009), 1900-2008 average precipitation data. Precipitation data for Lutz et al. (2014) have been increased by a factor of 1.17, as used in their study. **Modelled runoff is based on a part (~20%) of the Shigar basin. Bocchiala et al. (2011) have modelled/projected precipitation in the Shigar watershed based on Winiger et al. (2005) proposed projection parameters. Immerzeel et al. (2013) have used modelled precipitation (1961-1990) based on precipitation lapse rate (0.21% increase in precipitation with every meter increase in altitude) derived in the Hunza basin for neutral mass balance as presented in Immerzeel et al. (2012). Immerzeel et al. (2013), Bookhagen and Burbank (2010) have not calibrated their models for the gauge flows, and used calibration parameters from the eastern Himalayan sub-basins. All values are based on respective studies along with additional data and results provided by authors of Lutz et al. (2014a) and Mukhopadhyay (2012).

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