Dear Prof. Yongqiang ZHANG,

Thank you very much for your valuable comments. These helpful suggestions will help us improve this manuscript significantly. Following is the point to point reply.

This manuscript comprehensively reviews hydrological modelling conducted in glacierized catchments in Central Asia. It is a very interesting synthesis focusing on the current limits, challenges and directions of hydrological modelling. The authors point it out that it is lack of glacier submodel and points directions for future hydrological modelling in those regions. The manuscript reads well. I recommend the manuscript to be accepted by HESS after a moderate to major revision is conduced. Following are my critical suggestions/comments for improving its quality.

1. Glacierized catchments in Central Asia should be delineated. I cannot find spatial distribution of each catchment.

Response: The boundary of each catchment included in our study was added in the revised Figure 1 based on the DEM derived flow direction. Glacier information was obtained from RGI (Randolph Glacier Inventory).

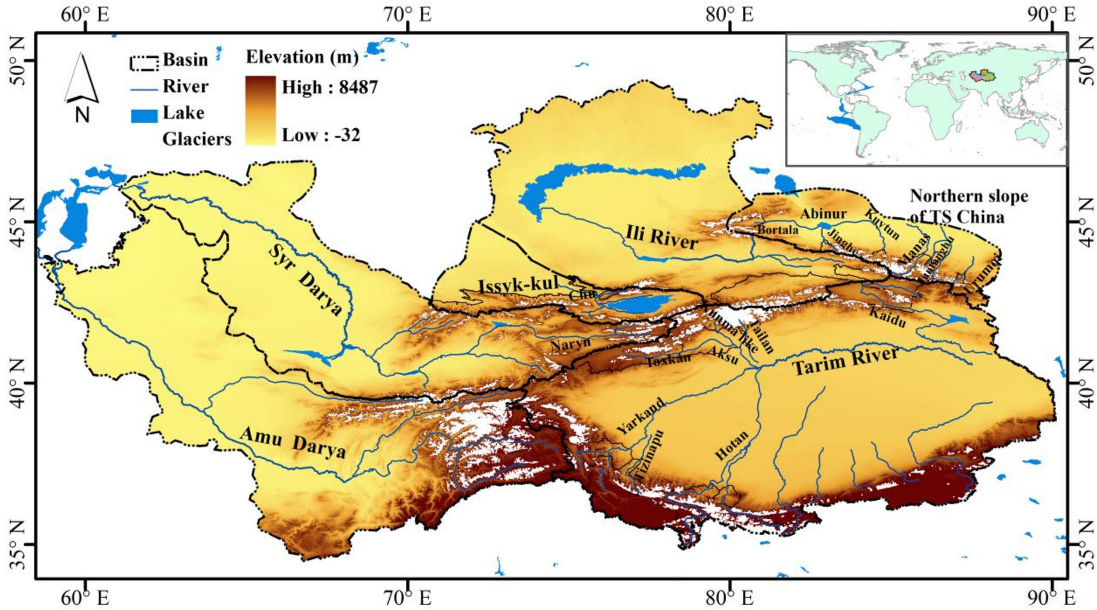

Figure 1: Map of Central Asian headwaters with main river basins or hydrological regions, namely the Tarim River Basin, the watersheds in the northern slope of the Tienshan Mountains, the Issyk Lake Basin, the Ili River Basin, the Amu Darya and the Syr Darya Basins. Lake outlines are from Natural Earth (http://www.naturalearthdata.com/). River system is derived based on elevations of SRTM 90 m data. Glacier information was obtained from RGI (Randolph Glacier Inventory).

2. Need a table summarising attributes of the major catchments (i.e. Ili River, the Amu Darya, the Syr Darya, Tarim River, etc), including climate, soil, vegetation and glacier ratio, etc.

Response: Thank you for your advice. We added Table 1 summarizing the attributes of the major catchments.

Table 1: Summary of climatic and underlying conditions of the basins. The topography is based on SRTM data, glacier data is from RGI (Randolph glacier inventory), and climate is based on the world map of the Koppen-Geiger climate classification. Vegetation is from the land use data from Xinjiang institute of Ecology and Geography.

Catchment	Tarim River Basin	Catchments in northern TS China	Issyk Lake Basin	Ili River Basin	Amu Darya Basin	Syr Darya Basin
Location	Surrounded by the Tienshan Mountains and the Kunlun Mountains	Northern Tienshan	Western Tienshan	Western Tienshan Valley	Western Tienshan and Pamir	Western Tienshan
Topography						
Basin area (km^2)	868,811	126,463	102,396	429,183	674,848	442,476
Percentage of elevation > 3000m (%)	28.00%	13.80%	14.50%	4.60%	20.50%	9.50%
Glaciation area (km^2)	15789	1795	994	2170	9080	1850
Climate						
Dominant climate	Arid cold	Arid cold	Arid cold; continental	Arid cold; continental	Arid cold; snow	Arid cold
Vegetation						
Forest percent (%)	0.7	10.4	6.4	4.1	10.9	2.5
Pasture percent (%)	16.7	14.5	31.2	28.6	19.4	17.3
Percent of water, snow, ice (%)	5.4	3.9	7.8	5.3	5.3	2.8

3. Table 1 should be more explicit. Please separate catchments to hydrological model. This table needs to match the table I recommend in point 2. Reviewers can then easily find catchments where how many hydrological modeling studies have been carried out in literature.

Response: Thank you for your valuable suggestions. We separated the models for each catchment (including each sub-catchment) in Table 2.

Table 2: Summary of hydrological modeling in glacierized central Asian catchments

Catchments	Models	Major conclusions	Innovations and Limitations	References
Tarim River				
Tarim River Basin	Modified two-parameter semi- distributed water balance model	Improved the original two-parameter monthly water balance model by incorporating the topographic indexes and could get comparable results with the TOPMODEL model and Xin'anjiang model.	Less input data are required; Lack of glacier and snowmelt processes.	(Peng and Xu, 2010; Chen et al., 2006)
	TOPMODEL model	In the Aksu River, runoff was more closely related to precipitation, while in the Hotan River, it was more closely related to temperature.		
	Xin'anjiang model	Runoffs of the Aksu, Yarkand and Hotan river exhibited increasing tendencies in 2010 and 2020 under different scenarios generated from the reference years.		
	Projection Pursuit Regression (PPR) model	If temperature rises 0.5-2.0 ℃, runoff will increase with temperature for the Aksu, Yarkand and Hotan River.	Lack of physical basis.	(Wu et al., 2003)
	VIC	For the Tarim River, runoff will decrease slightly in 2020-2025 based on HadCM3 under A2 and B2 when not considering glacier melt.	Lack of glacier module.	(Liu et al., 2010)
Tailan River	Modified degree-day model including potential clear sky direct solar radiation coupled with a linear reservoir model	Glacier runoff increases linearly with temperature over these ranges whether or not the debris layer is taken into consideration. The glacier runoff is less sensitive to temperature change in the debris covered area than the debris free area.	Considered the effect of solar radiation and quantified the debris effect.	(Zhang et al., 2007b)

Aksu River inclusing Kumalike and Toxkan River	Xin'anjiang model	Precipitation has a weak relationship with runoff in the Kumalike River.	Joined the snowmelt module. The model could not well capture the snowmelt/ precipitation induced peak streamflow.	(Wang et al., 2012a)
	VIC-3L model	Glacier melt, snowmelt and rainfall accounted for 43.8%, 27.7 and 28.5% of the discharge for the Kumalike River while 23.0%, 26.1% and 50.9% for the Toxkan River. For the Kumalike River and the Toxkan River, the runoff have increased 13.6% and 44.9% during 1970-2007, and 94.5% and 100% of the increases were attributed by precipitation increase. For the Kumalike River, glacier area will reduce by >30% resulting in decreased melt water in summer and annual discharge (about 2.8%–19.4% in the 2050s).	The model performance was obviously improved through coupling a degree-day glacier-melt scheme, but accurately estimating areal precipitation in alpine regions still remains.	(Zhao et al., 2013; Zhao et al., 2015)
	SWIM model	The model is capable to reproduce the monthly discharge at the downstream gauge well using the local irrigation information and the observed upstream inflow discharges. About 18% of the incoming headwater resources consumed until the gauge Xidaqiao, and about 30 % additional water is consumed along the river reaches between Xidaqiao and Alar. Different irrigation scenarios were developed and showed that the improvement of irrigation efficiency was the most effective measure for reducing irrigation water consumption and increasing river discharge downstream.	Investigated the glacier lake outburst floods using a modeling tool in the Aksu River. Inclusion of an irrigation module and a river transmission losses module of the SWIM model. Model uncertainties are largest in the snow and glacier melt periods.	(Huang et al., 2015; Wortmann et al., 2014)
	WASA model	Glacier melt contributes to 35–48% and 9–24% for the Kumalike River and the Toxkan River. For the Kumalike River, glacier geometry changes lead to a reduction of 14–23% of streamflow increase compared to constant glacier geometry. —	The model considered changes in glacier geometry (e.g., glacier area and surface elevation). It used a multi-objective calibration based on glacier mass balance and discharge.	(Duethmann et al., 2015)
	The temperature and precipitation revised AR(p) model; NAM rainfall-runoff model	The AR(p) model is capable to predict the streamflow in the Aksu River Basin.	Needing less hydrological and meteorological data.	(Ouyang et al., 2007)
Kaidu River	MIKE-SHE model	Compared remote sensing data and station based data in simulating the hydrological processes. Remote sensing data is comparable to conventional data. RS data could partly overcome the lack of necessary hydrological model input data in developing or remote regions.	Missing glacier melt; Lack of observation to verify the meteorological condition in the mountainous regions.	(Liu et al., 2012a; Liu et al., 2013)
	HBV model	When the base runoff is 100 $m^3 s^{-1}$, the critical rainfalls for primary and secondary warning flood are 50 mm and 30 mm respectively for the Kaidu River.	It underestimated the peak streamflow while overestimated the base flow.	(Fan et al., 2014)
	SRM including potential clear sky direct solar radiation and the effective active temperature.	Spring streamflow is projected to increase in the future based on HadCM3.	Limited observations resulted in low modeling precision. The APHRODITE precipitation performed good in hydrological modeling in the Kaidu River.	(Zhang et al., 2007a; Zhang et al., 2008; Ma et al., 2013; Li et al., 2014).
	SWAT	Precipitation and temperature lapse rates account for 64.0% of model uncertainty. Runoff increases under RCP4.5 and RCP8.5 compared to 1986-2005 based on a cascade of RCM, bias correction and SWAT model.	Quantified uncertainty resulted from the meteorological inputs.	(Fang et al., 2015a; Fang et al., 2015c)
	Modified system dynamics model	Simulations of low-flow and normal-flow are much better than the high-flow, and spring-peak flow are better than the summer pecks in the Kaidu River.	The modified model was robust by modified snowmelt process and soil temperature for each layer to describe water movement in soil.	(Zhang et al., 2016)

Yarkand river	MIKE-SHE model	Simulated snow pack using station data differs significantly from that using remote sensing data.	Lack of glacier moduld	Liu et al., 2016b
	Integrating Wavelet Analysis (WA) and back- propagation artificial neural network (BPANN)	Runoff presented an increasing trend similar with temperature and precipitation at the time scale of 32-years. But at the 2, 4, 8, and 16-year time-scale, runoff presented non-linear variation.	Interpreted the nonlinear characteristics of the hydro-climatic process using statistic method.	(Xu et al., 2011; Xu et al., 2014;)
	Degree-day model	Decreasing rate of glacier mass was 4.39 mm a^{-1} resulting in a runoff increasing trend of 0.23×10^{8} m^{3} a^{-1} during 1961 - 2006. Sensitivity of mass balance to temperature is 0.16 mm a^{-1} ℃$^{-1}$. Glacier runoff will increase 13%-35% during 2011-2050 compared to 1960-2006 with obvious increase in Summer.	The glacier dynamics are considered and the area–volume scaling factor is calibrated using remote sensing data.	(Xie et al., 2006; Zhang et al., 2012a; Zhang et al., 2012b)
Tizunafu River	SRM including snow albedo	It could well simulate the runoff of the Tizinapu River. Runoff is dominated by precipitation and temperature lapse rates and snow albedo.	Lack of glacier module.	(Li and Williams, 2008)
Hotan River	Integrating Wavelet Analysis (WA) and back- propagation artificial neural network (BPANN)	For the Hotan River, runoff correlates well with the 0 ℃ level height in summer for the north slope of Kunlun Mountains.	Interpreted the nonlinear characteristics of the hydro-climatic process.	(Xu et al., 2011)
Catchments in northern slope of TS China				
Manas River	1) SWAT model 2) SRM model 3) EasyDHM model	1) Glacier area decreased by 11% during 1961-1999 and glacier melt contributes 25% of discharge. 2) Better simulation of snowmelt runoff than rainfall–runoff by the SRM.	1) Both the glacier melt module and two-reservoir method were included in the hydrological simulations. 2) Snow cover calculation algorithm is added to validate model performance.	SWAT: (Yu et al., 2011; Luo et al., 2012; Luo et al., 2013; Gan and Luo, 2013) SRM: (Yu et al., 2013) EasyDHM: (Xing et al., 2014)
Urumqi River	1) Isotope Hydrograph Separation (IHS) 2) water balance model 3) HBV model 4) Exponential regression 5) SRM model 6) THmodel model	1) Runoff has risen by 10.0% during 1950-2009; Glacier melt water contributes to 9% of runoff. 2) The cumulative mass balance of the glacier was -13.69 m during 1959-2008; proportion of glacier runoff increased from 62.8% to 72.1%. 3) For a glacierized catchment (18%), the discharge will increase by 66±35% or decrease by 40 ±13% if the glacier size keeps unchanged or glacier disappears in 2041-2060. 4) Glacier runoff is critically affected by the ground temperature.	1) The IHS method has overwhelming potential in analyzing hydrological components for ungauged watersheds. 2) Focusing on the glacierized and ablation area. 3) Considering future runoff under different glacier change scenarios. 4) This study shed light on glacier runoff estimation based on ground temperature for data scarce regions. 5) Calculated the curve of snow cover shrinkage based on MODIS data. 6) An energy balance model is proposed to close the balance equation of soil freezing and thawing.	(Kong and Pang, 2012; Sun et al., 2013; Sun et al., 2015b Chen et al., 2012; Huai et al., 2013; Mou et al., 2008;)
Ebinur Lake Catchment including Jinghe River, Kuytun River and Bortala River	SWAT model and the sequential cluster method Runoff Controlled Auto Regressive (CAR) model	For the Jinghe River, 85.7% of the runoff reduction is caused by human activity and 14.3% by climate change. Runoff of three rivers in Ebinur Lake catchment exhibited different changes: Jinghe River and Kuytun River exhibited a slightly increasing trend, but an adverse trend in the Bortala River. In a warm-humid scenario, runoff in the Jinghe River and Bortala River will increase, it will decrease in the Kuytun River.	Identified the effects of human activities and climate change on runoff. The CAR is based on past and present values without physical basis.	(Dong et al., 2014; Yao et al., 2014)
Juntanghu Basin:	Distributed Snowmelt Runoff Model (DHSVM)	The coupled WRF and DHSVM model could predict 24h snowmelt runoff with relative error within 15%.	MODIS snow cover and the calculated snow depth data are used in the snowmelt runoff modeling.	(Zhao et al., 2009)

Issyk Lake Basin				
Small rivers around the Issyk Lake	Degree-day approach	Runoff contribution is varying in a broad range depending on the degree of glacierization in the particular sub-catchment. All rivers showed a relative increase in annual river runoff ranging between 3.2 and 36%.	The glacier melt runoff fraction at the catchment outlet can be considerably overestimated.	(Dikich and Hagg, 2003)
Chu River	SWAT-RSG model	General decrease was expected in glacier runoff (–26.6% to –1.0%), snow melt (–21.4% to +1.1%) and streamflow (–27.7% to –6.6%); Peak streamflow will be put forward for one month.	Use the glacier dynamics and assessed the model performance based on both streamflow and glacier area.	(Ma et al., 2015)
Ili River Basin				
Gongnaisi River	SRM model	For the runoff is sensitive to snow cover area and temperature. If temperature increases 4 ℃, the runoff will decrease by 9.7% with snow coverage and runoff shifting forward.	SRM is capable to model the snowmelt runoff.	(Ma and Cheng, 2003)
Tekes River	SWAT model	Glaciers retreated about 22% since 1970s, which was considerably higher than the Tianshan average (4.7%) and China average (11.5%), resulting in a decrease of proportion of precipitation recharged runoff from 9.8% in 1966-1975 to 7.8% in 2000-2008.	Using two land use data and two Chinese glacier inventories, the model could well reproduce streamflow.	(Xu et al., 2015)
Ili River	MS-DTVGM model	Daily runoff correlated closely with snowmelt, suggesting a snowmelt module is indispensable.	This method reduced dependence on conventional observation, and was applied to the Ili River basin where traditional data are scarce.	(Cai et al., 2014)
	Water Balance	Water decrease in 1911-1986 in the middle and lower reaches of the Lake Balkhash is due to decreased rainfall and reservoirs storage.	—	(Kezer and Matsuyama, 2006; Guo et al., 2011)
Amu Darya and Syr Darya Basin				
Amu Darya and Syr Darya Basin	STREAM	The runoff of the Syr Darya declined considerably over the last 9000 years. For the Amu Darya and Syr Darya Basin, the glacier covered areas have decrease 21% and 22% in 2001-2010 compared to the baseline (1960-1990). The runoff of the Syr Darya is not so sensitive to future warming compared to the past 9000 years. For the Amu River Basin, 20-25% of the glaciers will retain under a temperature increment being 4-5 ℃ and precipitation increase rate being 3%/℃. For the Syr Darya, runoff under the A2 and B2 scenarios will increase 3%-8% in 2010-2039, with sharpened spring peak and a slight lowered runoff from late June to August.	Simulated long term discharge for the Holocene and future period. The model includes the calculation of rainwater, snowmelt water and glacier runoff (based on the glacier altitude and equilibrium lime altitude).	(Aerts et al., 2006; Savoskul et al., 2003; Savoskul et al., 2004; Savoskul et al., 2013)
	AralMountain model	For the Amu Darya, glacier melt and snowmelt contribute to 38% and 26.9% of runoff, while for the Syr Darya, the proportions are 10.7% and 35.2%. Glacier retreat by 46.4% - 59.5% depending on selected GCM. For the Syr Darya, average water supply to the downstream will decrease by 15% for 2021-2030 and 25% for 2041-2050. For the Amu Darya the expected decreases are 13% (2021-2030) and 31% (2041-2050).	Fully simulated the hydrological processes.	(Immerzeel et al., 2012a)
Test sites "Abramov" in SyrDarya and "Oigaing" in Amu Darya	HBV-ETH and OEZ model	Overall good model performances were achieved with the maximum discrepancy of simulated and observed monthly runoff within 20 mm. General enhanced snowmelt during spring and a higher flood risk in summer are predicted under a doubling atmospheric CO_2 concentration with greatest runoff increases occurring in August for the highly glaciated catchments and in June for the Nival catchment.	It considered geographical, topographical and hydrometeorological features of test sites, and reduced modeling uncertainties. This procedure requires a lot meteorological and land surface data and knowledge of the modeler.	(Hagg et al., 2007)

Panj River	HBV-ETH	For the upper Panj catchment, the current glacier extent will decrease by 36% and 45%, respectively, assuming temperature increment being 2.2 ℃ and 3.1 ℃.	Application of glacier parameterization scheme.	(Hagg et al., 2013)
Naryn River	SWAT with glacier module	Glacier area has decreased 7.3% during 1973-2002. Glaciers will recede with only 8% of the small glaciers retain by 2100 under RCP8.5 and net glacier melt runoff will reach peak in about 2040 and decrease later.	Incorporated glacier dynamics and validated the model using two glacier inventories.	(Gan et al., 2015)
Syr Darya	NAM model with a separate Land-ice model	Glacier volume will lose 31%±4% under SRES A2 until 2050s, and the runoff peak will shift forward by 30–60 days from the current spring/early summer towards a late winter/early spring runoff regime.	The NAM model was improved to be robust using only five freely calibrated parameters.	(Siegfried et al., 2012)

4. Table 1 can be clear by reorganisation. Following is just an example. Catchment study hydrological modelling submodels major conclusions limit.

Response: We have updated Table 1 according to your comment. Please refer to the responses to Point 3 above.

5. Need more discussion on how to improve glacier melt simulation. In section 3.2 Glacier melt, authors point that major challenge for glacier melt simulation includes lack of glacier variation data and lack of glacier mass balance data. It looks that it is a widely existed issues for hydrological modelling in high-elevation and high-latitude regions. The question is how hydrologists can improve glacier melt simulations. I think that author can have more in-depth discussion in Section 4 (i.e. if the observations incorporate into remote sensing observation to improving glacier melt observation; model parametrization to balance equifinality and submodels; which kind of glacier models should be applied for), which will really benefit this manuscript.

Response: Thanks for your comment.

In the revised manuscript, we discussed more thoroughly on how to improve the glacier melt simulation based on the present publications. First of all, Section 4.2 stressed the significance of integrated use of multiple dataset, e.g., remote sensing data, isotope tracer, observed single glacier mass balance. Section 4.3 expresses the same idea of "model parameterization". We try to emphasize the significance of multi-objective calibration and validation to handle the "equifinality" effects, especially when one or several modules are missing. In addition, some discussions are taken on the current and future development of hydrological models for the Tienshan Mountains.

4.2 Integration of different data sources

After appropriate preprocessing, several types of data, including remote sensing and reanalysis, could be used in hydrological modeling, as Liu et al. (2013) indicated that remote sensing data could reproduce comparable results with the traditional station data. In recent years, isotope data are increasingly used to define water components (Sun et al., 2016) and it would be a fortune for hydrologists to validate their models, or even calibrate the models (Fekete et al., 2006). The overall idea here is to build and integrate more comprehensive datasets in order to improve hydrological modeling. An example of this approach can be found in Naegeli et al. (2013), who attempted to construct a worldwide dataset of glacier thickness observations compiled entirely from a literature review.

4.3 Multi-objective calibration and validation

A hydrological model should not just ”mimic” observed discharge but also reproduce snow accumulation and melt dynamics or the glacier mass change (e.g. Konz and Seibert, 2010). As discussed previously, hydrological models that are calibrated based on discharge alone may be of high uncertainty and even “equifinality” for different parameters or inputs. This could happen especially when one or several modules are missing. For example, one might overestimate the mountainous precipitation or underestimate the evapotranspiration if the glacier melt module is missing. Therefore, it is suggested to account for each hydrological component as much as possible. We strongly suggest the use of multi-objective functions and multi-metrics to calibrate and evaluate hydrological models. Compared to single objective calibration, which was dependent on the initial starting location, multi-objective calibration provides more insight into parameter sensitivity and helps to understand the conflicting characteristics of these objective functions (Yang et al., 2014). Therefore, use different kinds of data and objective functions could improve a hydrological model and provide more realistic results.
For the data-scarce Tienshan Mountains, however, we do not recommend an over-complex or physicalized modelling of each component as lack of validation data which may result in equifinality discussed previously when the climate system stays stable. The more empirical models (enhanced temperature index approaches) could reproduce comparable results with the sophisticated, fully-physical based models (Hock, 2005). What worth mentioning is that, the physically-based glacier models are more advancing when quantify future dynamics of glaciers and glacier/snow redistribution when the climatic and hydrologic systems are not stable (Hock, 2005). The physical models should be further developed and used in glacier modelling as long as there is enough input and validation data

6. Line 270. Semicolon should be after ‘ text’.

Response: We have corrected it.