LETTER

Effects of cryospheric hydrological processes on future flood inundation and the subsequent socioeconomic exposures in Central Asia

Ning Wang, Fubao Sun, Hong Wang, and Wenbin Liu

1 Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, People’s Republic of China
2 State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi, People’s Republic of China
3 Akesu National Station of Observation and Research for Oasis Agro-ecosystem, Akesu, People’s Republic of China
4 College of Resources and Environment, University of Chinese Academy of Sciences, Beijing, People’s Republic of China

* Authors to whom any correspondence should be addressed
E-mail: wanghong@igsnrr.ac.cn and liuwb@igsnrr.ac.cn

Keywords: cryospheric hydrological process, flood simulation, flood inundation, socioeconomic exposure, Central Asia

Abstract
Floods and their subsequent socioeconomic exposures are increasing in most parts of the world due to global warming. However, less attention is given in the arid Central Asia (CA), in which floods usually occur in data-scarce high-mountainous regions with complex cryospheric hydrological processes (CHP). In this study, an improved hydrologic-hydrodynamic model coupled with a glacier mass balance module was developed to enhance flood simulations in CA. The effects of the CHP on future flood inundation and the subsequent socioeconomic exposures were also investigated. We found that the simulations of daily streamflow and flood magnitudes improved significantly over the selected hydrological stations after considering the glacier mass balance. Our estimations indicated that the flood inundation and its dynamic evolution generally agreed with satellite observations. Moreover, CHP-induced (rainfall-induced) flood inundation plays a significant role in China’s Xinjiang and Tajikistan (other regions of CA). The CHP would amplify the effects of future flood on socioeconomics in CA, with population (Gross Domestic Productivity, GDP) exposure up to 2.25 million persons/year (150 billion $ PPP/year) for 2071–2100. These findings could provide scientific evidence to improve the understanding of CHP effects on future floods and the subsequent exposures, informing the prioritization and design of flood mitigation strategies in CA.

1. Introduction
Central Asia (CA) is a typical arid region, which includes Kazakhstan (KAZ), Kyrgyzstan (KGZ), Tajikistan (TJK), Turkmenistan (TKM), Uzbekistan (UZB) and China’s Xinjiang (XJI). In the last 70 years, CA experienced a more intensified climate warming with temperature increase at a rate of 0.30 °C/decade, which was higher than the global average of 0.22 °C/decade (Huang et al 2012, Yan et al 2021, Yao et al 2021). Global warming is expected to increase flood frequency by altering precipitation intensity and the melting rate of glacier and snow in CA (Thober et al 2018, Swain et al 2020). However, seasonal floods in arid CA did not receive insufficient attention, although they have caused serious socioeconomic losses (Thurman 2011). For example, in Tajikistan (TJK), the 1992 flood caused over 1300 fatalities and about $500 million damage (nearly 23% of TJK’s 1992 GDP, World Bank Group (2016)), while the 2015 flood (caused by the rapid melting of glaciers and snowfields as result of a summer heat wave) led to an economic loss of more than $600 million (Pohl et al 2017). The 1993 flood in...
Turkmenistan (TKM) resulted in an economic loss of about $200 million, which was approximately 6% of TKM’s 1993 GDP (World Bank Group 2016).

Currently, researchers focus mostly on global flood risk assessment using global hydrological models or land surface models (Liu et al. 2021, Smith et al. 2019, Yang et al. 2019, Gu et al. 2020, Boulange et al. 2021, Tanoue et al. 2021), which have considerable uncertainties in regional analysis due to their limited physical interpretation of regional hydrological processes and relatively coarse spatiotemporal resolution. It is especially true in CA. The streamflow originates mainly from high mountain regions with complex cryospheric hydrological processes (CHP, e.g. snow or glacier melt; Zhang et al. 2016, Fang et al. 2018), which also plays a significant role in flood evolution. Moreover, a clear distinction between the effects of CHP and rainfall on flood inundation and their socioeconomic exposures in CA is critical for governments and the public to take corresponding measures to adapt to, or mitigate, flood threats. To our best knowledge, few studies have been conducted in CA to describe flood dynamics and further distinguish the effects of CHP or rainfall on their socioeconomic exposures due to data scarcity and inadequate flood simulations. Some studies have attempted to improve the understanding of CHP by taking dynamic of snow and glacier into consideration (Shen et al. 2018, Shaw et al. 2020), by integrating either degree-day formula (Zhang et al. 2013, Lutz et al. 2014, Chandel and Ghosh 2021) or energy (Zhao et al. 2013, Ren et al. 2018) balance into hydrological model. The latter is usually data intensive and difficult to apply in a large-scale and data-scarce region like CA. The former is relatively simpler but sometimes more effective, which is thus a feasible way to improve descriptions of CHP in hydrological models in the data-scarce CA.

In this study, we focus on investigating the effects of CHP on flood dynamics and the subsequent socioeconomic exposures in CA in the context of climate warming and socioeconomic development. First, an improved hydrologic-hydrodynamic modeling framework coupled with a glacier mass balance module (HHMFg) was constructed and validated against observed daily streamflow and the satellite-retrieved flood extents. Second, the contributions of CHP to flood inundation and the subsequent socioeconomic exposures were quantified. The results are expected to provide a deeper understanding of the effects of CHP on future floods in CA.

2. Data and methodology

2.1. Data and model description

We apply meteorological products (Mp, table S1) to force the hydrological modelling. Due to the uncertainties of the Mp, especially in alpine regions, we use in situ observation (Mobs) to bias-correct Mp based on the precipitation gradient (Pg) and lapse rate (Lr) (see more details in table S2 and Wang et al. 2021). Global climate model outputs (MGM), obtained from the Inter-Sectoral Impact Model Intercomparison Project 3b (ISIMIP 3b, Lange 2019, Cucchi et al. 2020) under 3 Shared Socioeconomic Pathway-based Representative Concentration Pathway (SSP) scenarios (SSP126, SSP370 and SSP585), are used to project flood dynamic. Glacier extent data (Gext, table S1) are used to initialize the glacier mass balance module of the HHMFg. Soil, land use and digital elevation model data which are necessary for hydrological model are obtained from the sources described in Wang et al. 2021. Moreover, we adopted observed daily streamflow (Qobs) and land surface water extent data (obtained from MODIS Daily Water (MODIS) and Global Surface Water (GSW), see Supplementary Note and table S1, interpolated into 11′) to evaluate the performances of the HHMFg. In total, 15 hydrological stations (figure 1) are selected for calibration (mostly) and validation (some). Population (POP) and GDP projections (table S1), which are compatible with the SSFs, are selected to assess the socioeconomic exposures to flood in CA. Two 30 year periods (1971–2000, hereafter 20 C, and 2071–2100, hereafter 21 C) are selected to represent the historical and future conditions, respectively.

An improved HHMFg was developed to simulate flood inundation maps (Fldare) across the CA. The HHMFg comprises two models, an improved VIC-GM2 hydrological model considering CHP and the Catchment-based Macro-scale Floodplain model (CaMa-Flood, Yamazaki et al. 2011, 2013) (see details in supplementary note).

2.2. Flood event, model evaluation, and flood exposure

Flood duration is identified using the threshold of 95th percentile daily streamflow during 20 C (Q95). To avoid repetitively counting the same flood event twice or more, we adopt the method of Lang et al. (1999) as shown in equation (1), which has been reported to reliably identify consecutive flood events (Wang et al. 2021).

\[ \theta > 5 + \ln(A) \] (1)

where \( \theta \) is the interval time between two flood events (day) and \( A \) represents the area (km²). If the interval days between consecutive flood events do not reach \( \theta \), it is considered as a single flood event.

We adopt the Nash-Sutcliffe efficiency coefficient (NS) (Nash and Sutcliffe 1970), Kling-Gupta efficiency (KGE) (Gupta et al. 2009), Pearson correlation coefficient (R), percentage bias (PBIAS) and probability of detection (POD) (Wu et al. 2012)
to evaluate the daily streamflow, \( Q_{95} \) and flood inundation simulations of the HHMF. More detailed information of these evaluation indicators can be found in supplementary note.

Flood exposure, which is widely used in assessing the effects of floods on socio-economic system (i.e. population and GDP) (Smith et al 2019, Tellman et al 2021), is defined as the summing pixel values of all grid cells where the Fldare intersects the socioeconomic scenario map (POP and GDP). Fldare related to the flood events is extracted from the flood depth results of the HHMF by using a 10 cm depth threshold (whereby all grid cells with a depth < 10 cm are set to zero). It should be noted that river channels are always considered to be inundated. Moreover, we also define alternative scenarios to differentiate the effects of climate change (CC) and the combined impact of climate change and socioeconomic development (SC). Specifically, the POP and GDP are fixed to that of the base-year 2000 in the CC scenario, while both climate and socioeconomic (POP and GDP) changes are accounted for in the SC scenario.

3. Results

3.1. Model validation

The streamflow simulated by the HHMF forced by bias-corrected M at selected hydrological stations is shown in figure 2, where it can be concluded that the simulation results are reliable. Specifically, the NSs (KGEs) for all listed stations exceed 0.64 (0.67), with most stations performing very good (NSs > 0.7, KGEs > 0.8). Meanwhile, the values of \( R \) exceed
0.85 and the PBIASs for most stations are within the range of 10%, indicating a good correlation. We find a large improvement in flood simulation after considering glacier mass balance ($Q_{95,avg}$, figure S1) for all stations, which indicates the importance of glacier mass balance to CA. In addition, we find that the $Q_{95,avg}$ at selected hydrological stations with large (i.e. AmKer, Alaer) or small (i.e. YlTal) control basin area is not as good as the others. This may be caused by anthropogenic activities (e.g. irrigation water intake, dam construction, and reservoir regulation) or coarse spatial resolution and needs to be further explored in future work. Overall, the tendencies and magnitudes of simulated streamflow and floods are well presented and considered satisfactory.

### 3.2. Flood inundation

The spatial distribution of POD calculated from Fldare and MOIDS over CA during 2001–2007 is obtained (figure 3(a)). We also count the proportion of POD = 1 (red) and POD = 0 (blue) in different regions, as shown in the 100% stacked bar graph in the upper right corner of figure 3(a), which indicates that the flooded areas detected by MODIS are well captured by the HHMF$_g$. The proportion with POD = 1 in each region of CA exceeds 70%, especially in TKM (87.6%). However, about 27% of flooded areas in UZB and KAZ remain undetected by the HHMF$_g$, which is mostly concentrated in flat areas. This point echoes the conclusion mentioned in section 3.1, where stations controlling a large basin area may introduce great uncertainties caused by anthropogenic activities (e.g. irrigation water intake, dam construction, and reservoir regulation). Moreover, topography over flat areas that are inaccurately described in CaMa-Flood (McClellan et al 2020) and exclusion of small surface water in the HHMF$_g$ may also shed light on this point.

To show more details of flood inundation area and to better compare with MODIS, we select and zoom in three typical inundated areas (I, Aral Sea region (b, MODIS; e, HHMF$_g$), II, Balkhash Lake basin (c, MODIS; f, HHMF$_g$) and III, Tarim River basin (d, MODIS; g, HHMF$_g$)), as shown in figure 3. Through comparison, we find that MODIS could not fully capture flood inundation that occurred in the river network, which may be justified by influences of land use conditions, cloud cover, and satellite repeat cycle (Ji et al 2018, Boergens et al 2019, Shin et al 2020), while Fldare could get rid of these constraints and accurately describe the spatial pattern of flood inundation. It can be seen in figures 3(e)–(g) that the flood inundation is mainly concentrated in places where the river network is dense, while it is smaller in the upper reaches. In addition, we repeat a similar comparison between Fldare and GSW for the period 1989–2007 to support the above conclusions, as shown in figure S2. Noted that the maximum annual

---

**Figure 2.** Observed (black line) and simulated (red line) daily (the superscript * represents monthly) streamflow over the 15 hydrological stations (located in figure 1). Noted that daily streamflow in stations (d) and (k) is missing.
extended flood inundation is chosen for comparison, as the daily- and monthly-scale data of GSW in CA are partially missing. Figure S2 confirms the point that the HHMF\textsubscript{g} could capture flooded areas well, with the proportion of POD = 1 exceeding 75%. Moreover, the fact that MODIS and GSW cannot fully capture flood inundation occurring in river networks shows that the surface water identification algorithm needs to be further improved. Overall, the good performance of the HHMF\textsubscript{g} informs us that it is reliable for investigating future flood inundation and their subsequent socioeconomic exposures in CA.

3.3. Contributions of cryospheric hydrological processes to future flood inundation

To better understand the contribution of CHP to future flood inundation, we use M\textsubscript{GCM} to drive the HHMF\textsubscript{g} with well-calibrated parameters (table S2) and count monthly average flood inundation areas in CA for 20°C and 21°C under different SSPs scenarios (figure 4). It should be noted that flood inundation areas in every country or region are segmented into rainfall-contributed, which is obtained from the simulated results of HHMF\textsubscript{g} with the glacier mass balance module off, and CHP-contributed, which is obtained by the Fldare minus rainfall-contributed areas. We identify that flood inundation in XJI is jointly induced by CHP and rainfall, with CHP playing the most important role. Moreover, flood inundation in TJK is dominated by CHP-induced, which may be caused by the fact that most areas of TJK are alpine regions and precipitation mainly exists in the form of snowfall, while in other countries it is rainfall-induced. Specifically, CHP-contributed annual average flood inundation in XJI (TJK) accounts for about 72% (93%), 69% (81%) and 69% (80%) of the total flood inundation area in 21°C under SSP126, SSP370 and SSP585, respectively. Flood inundation in CA reaches maximum in August and would occur earlier under climate change, especially under the SSP585 scenario.
Figure 4. Comparison of rainfall-contributed (red) and CHP-contributed (blue) monthly average flood inundation area (km$^2$) in different regions of CA for 20 C (Hist) and 21 C (SSP126, SSP370 and SSP585).

Compared to flood inundation under the SSP370 (SSP585) scenario in CA, it can be seen that adopting sustainable strategies (SSP126) would benefit the most in reducing flood inundation in 21 C, with reductions of 36% (43%) for CHP-contributed and 43% (49%) for rainfall-contributed, respectively.

3.4. Cryospheric hydrological processes amplify future socioeconomic exposures

To highlight the importance of CHP to future flood exposures in CA, we compare relative changes (figure 5) and absolute values (figure 6) of socioeconomic exposure with or without consideration of CHP between 20 C and 21 C in the CC and SC scenarios. We find that lack of consideration of CHP in CA would falsely amplify relative changes in socioeconomic exposure to flood between 20 C and 21 C in the CC scenario, especially in TJK with a false magnification of 320 (110) for population (GDP) exposure, as shown in figures 5(a) and (c). Moreover, the false amplification of relative changes is significantly decreasing in the SC scenario (figures 5(b) and (d)) compared to those in the CC scenario, which indicates that socioeconomic development plays an important role.

In the CC scenario, climate change induced-flood (with consideration of CHP) increases population (GDP) exposure by 1.1–3.0 (5.4–11.3) times, from
Figure 5. Relative changes (unit: times) in annual average population (POP, (a, b)) and GDP (c, d) exposure to floods without consideration of CHP (y axis, NCHP) between 21°C and 20°C, \((21°C - 20°C) \times 100/20°C\), against those with consideration of CHP (x axis) under different scenarios, where x represents annual average affected population or GDP. Different shapes (colors) represent different regions (SSPs scenarios). The dashed line represents the ratio line.

Figure 6. Population (a, c) and GDP (b, d) exposure to floods with considering CHP (first row) and without considering CHP (second row) in CA for 20°C (Hist) and 21°C (SSP126, SSP370 and SSP585) in the CC (yellow) and SC (red) scenarios. The figures in the upper left corner of (b, d) represent GDP exposure to floods for 21°C in the SC scenario. PPP refers to purchasing-power parity.
20 C to 21 C in CA. Specifically, KAZ would experience the most severe change in socioeconomic exposures than other regions in CA, with a maximum increase of 3.9 (14.6) times in population (GDP) exposure from 20 C to 21 C. While in the SC scenario, future socioeconomic exposure increases even more, which suggests that population and GDP growth play major roles in flood exposure in CA under global change. Specifically, UZB (XII) would experience the most severe change of population (GDP) exposure than other regions in CA.

Figure 6 also confirms the importance of CHP to future flood exposures in CA, which shows that absolute values of flood exposures in CA would be significantly underestimated when CHP is ignored (figures 6(c) and (d)). We find that CHP amplifies the effects of future floods on socioeconomic exposures in CA, especially in the SC scenario. Specifically, population (GDP) exposure to floods with considering CHP over 21 C under SSP370 (SSP585) in the SC scenario is 2.25 million persons/year (150 billion $ PPP/year), much higher than that without considering CHP with a value of 0.87 million persons/year (56 billion $ PPP/year). It should be noted that the population exposures under SSP126 and SSP585 in the SC scenario are less than that in the CC scenario (figure 6(a)), both are caused by the fact that the population of CA in 21 C is reduced compared to that in 20 C. Population exposure without consideration of CHP under SSP370 in the SC scenario is less than that in the CC scenario (figure 6(c)), while it is opposite when CHP is considered (figure 6(a)). This point could be explained by humans gradually moving from flood center areas to flood fringe areas in CA under SSP370. What’s more, we identify that adopting sustainable development strategies (SSP126) could effectively reduce future socioeconomic exposures to floods in CA.

4. Discussion

4.1. Comparison with existing studies

Although existing assessments of socioeconomic exposures to flood have typically been made on a global basis, and thus, encompass large uncertainties in regional analyses, we can still find some consistencies with our results. Changes in socioeconomic exposures to flood and hotspot regions with high flood exposure identified in this study (figures S3 and S4), are overall consistent with the results of recent existing studies (Alfieri et al 2017, Murnane et al 2017, Bernhofen et al 2021), despite different datasets, approaches and spatial scales (country level, basin level or grid level) used. However, some studies (Hirabayashi et al 2013, Kinoshita et al 2018) reported that CA would experience decreased flood exposures (population and GDP exposures) under climate change, as derived from simulations of an atmosphere-ocean general circulation model (AOGCM). This may be caused by the fact that these studies lack considerations of CHP and regional parameters optimization, which may result in poor or even erroneous conclusions. The above difference also highlights the importance of CHP on flood inundation in CA.

4.2. Uncertainties and limitations

The uncertainties in assessing flood exposures mainly originate from flood simulations. To decrease their impacts, we first bias-corrected the model-driven data by using Pg and Lr, which has been proven to be the most efficient approach in data-input bias-correction in CA (Shen et al 2018, Sun and Su 2020). In addition, multiple bias-corrected GCMs were applied, which has been confirmed that uses of multiple GCMs allow for the better synthesis of future projections than a single model and would help adjust the results to that of the observations (Maraun 2016, Liu et al 2021). Second, we improved the physical description of glacier mass balance processes (e.g. melt, sublimation and accumulation of glaciers) and constructed an improved modelling framework (HHMFg). Finally, multi-objective calibration (e.g. R, NS, KGE and PBIAS) and validation (e.g. streamflow and flood inundation) were also adopted to tackle the uncertainty. However, some uncertainties are inevitable due to the lack of high-precision flood inundation verification data and the lack of consideration of increased dam constructions in CA. Although the MODIS and GSW data were used to show that the flood inundation detected by them could be well captured by HHMFg, our simulated flood inundation in alpine regions with river channels was not reliably supported due to their unsatisfactory performance in these areas. Moreover, the increased dam constructions, which are used to satisfy the hydropower demand in upstream countries (Thurman 2011), may alter the flood pulse in the main stem (Orr et al 2012). Ignoring their effects on flood simulation potentially overestimated the flood inundation in downstream areas. Therefore, it is necessary to consider dam construction and reservoir regulation in optimizing model structure for a more realistic flood simulation in downstream areas in future work.

Furthermore, the socioeconomic exposure to future floods may be overestimated by using the predicted population and GDP data under different scenarios. This might be caused by the strong geographical assumptions that these data will not respond to flooding in terms of distribution. Nevertheless, it is considered robust that socioeconomic exposure to future floods in CA will increase and will be amplified by CHP.

4.3. Implications and future adaptations

Our work can be extended to evaluate the benefits of human adaptive behaviors in reducing socioeconomic exposures in CA. Even though we know
Acknowledgments

This research is financially supported by the National Natural Science Foundation of China (42025104 and 42022005), the Third Xinjiang Scientific Expedition (2022xjkk0102), the National Key Research and Development Program of China (2019YFA0606903), the Program for the ‘Kezhen-Bingwei’ Youth Talents (2020RC004 and 2021RC002) from the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, the Key Research Program of the Chinese Academy of Sciences (ZDRW-ZS-2019-3) and the Top-Notch Young Talents Program of China (Fubao Sun). We also thank the editor and anonymous reviewers for their helpful comments.

ORCID iDs

Ning Wang https://orcid.org/0000-0001-9020-8531
Wenbin Liu https://orcid.org/0000-0002-9569-6762

References

Alfieri L, Bisselink B, Dottori F, Naumann G, de Roo A, Salamon P, Wyser K and Feyen L 2017 Global projections of river flood risk in a warmer world Earths Future 5 171–82
Bernhofen M V, Trigg M A, Sleigh P A, Sampson C C and Smith A M 2021 Global flood exposure from different sized rivers Nat. Hazard Earth Syst. 21 2829–47
Boergens E, Dettmering D and Seitz F 2019 Observing water level extremes in the Mekong River Basin: the benefit of long-repeat orbit missions in a multi-mission satellite altimetry approach J. Hydrol. 570 463–72
Boulange J, Hanasaki N, Yamazaki D and Pokhrel Y 2021 Role of dams in reducing global flood exposure under climate change Nat. Commun. 12 1–7
Chandel V S and Ghosh S 2021 Components of himalayan river flows in a changing climate Water Resour. Res. 57 e2020WR027589
Cucchi M, Weerdon G P, Amici A, Bellouin N, Lange S, Müller Schmied H, Hershbach H and Buontempo C 2020 WFDE5: bias-adjusted ERA5 reanalysis data for impact studies Earth Syst. Sci. Data 12 2997–120
Fang G, Yang J, Chen Y, Li Z, Ji H and De Maeyer P 2018 How hydrologic processes differ spatially in a large basin: multisite and multiojective modeling in the tarim river basin J. Geophys. Res. 123 7098–113
Gu X, Zhang Q, Li J, Chen D, Singh V P, Zhang Y, Liu J, Shen Z and Yu H 2020 Impacts of anthropogenic warming and uneven regional socio-economic development on global river flood risk J. Hydrol. 590 125262
Gupta H V, Kling H, Beigh P A, Sampson C C and Smith A M 2021 Global flood exposure from different sized rivers Nat. Hazard Earth Syst. 21 2829–47
Hirabayashi Y, Mahendran R, Koirala S, Koshimba L, Yamazaki D, Watanabe S, Kim H and Kanase S 2013 Global flood risk under climate change Nat. Clim. Change 3 816–21
Huang J-F, Guan X-D and Ji F 2012 Enhanced cold-season warming in semi-arid regions Atmos. Chem. Phys. 12 5391–8

5. Conclusions

An improved hydrologic-hydrodynamic modeling framework with a glacier mass balance module (HHMFE) was constructed, for the first time, to investigate the effects of CHP on future flood inundation and the subsequent exposures in CA. We confirm that the improvement in flood simulations in CA is inseparable from the glacier mass balance processes. We find that CHP-induced (rainfall-induced) flood inundation contributes a lot in China’s Xinjiang and Tajikistan (in other regions of CA). We identify that ignoring the CHP in CA would falsely amplify the relative changes in socioeconomic exposure to flood. Moreover, the CHP amplifies the effects of future floods on socioeconomic exposures in CA, with a maximum POP (GDP) exposure of 2.25 million persons/year (150 billion $ PPP/year) over 21 C. These findings would provide scientific evidence on the effects of CHP on future flood exposures and indicate that more attention should also be given to floods beyond drought due to rapid socioeconomic development in CA.

Data availability statement

The in-situ meteorological data are obtained from http://data.cma.cn and www.knmi.nl/. The meteorological products can be downloaded from http://aphrodite.st.hirosaki-u.ac.jp/download/ and http://hydrology.princeton.edu/data.php. The ISIMIP3b datasets are downloaded from www.isimip.org/. The glacier extent data and the GRDC are available at www.glims.org/RGI/ and www.bafg.de/GRDC/EN/Home/homepage_node.html. The land surface water extent data can be available at http://data.ess.tsinghua.edu.cn/modis_500_2001_2016_waterbody.html and https://global-surface-water.appspot.com/download. Socioeconomic scenario data used in the SSP scenarios are available online (https://sedac.ciesin.columbia.edu and https://ilgshare.com).

All data that support the findings of this study are included within the article (and any supplementary files).
Ji L, Gong P, Wang J, Shi J and Zhu Z 2018 Construction of the 500–m resolution daily global surface water change database (2001–2016) Water Resour. Res. 54 10,270–92
Kinoshita Y, Tanoue M, Watanabe S and Hirabayashi Y 2018 Quantifying the effect of autonomous adaptation to global river flood projections: application to future flood risk assessments Environ. Res. Lett. 13 014006
Lang M, Ouarda T B M J and Bobee B 1999 Towards operational guidelines for over-threshold modeling J. Hydrol. 225 103–17
Lange S 2019 Trend-preserving bias adjustment and statistical downsampling with ISMIP3BASD (v1.0) Geosci. Model Dev. 12 3055–70
Liu W, Sun F, Feng Y, Li C, Chen J, Sang Y-F and Zhang Q 2021 Increasing population exposure to global warm-season concurrent dry and hot extremes under different warming levels Environ. Res. Lett. 16 094002
Liu W, Yang T, Sun F, Wang H, Feng Y and Du M 2021 Observation-constrained projection of global flood magnitudes with anthropogenic warming Water Resour. Res. 57 e2020WR028830
Lutz A F, Immerzeel W W, Shrestha A B and Bierkens M F P 2014 Consistent increase in high Asia’s runoff due to increasing glacier melt and precipitation Nat. Clim. Change 4 587–92
Maranu D 2016 Bias correcting climate change simulations—a critical review Curr. Clim. Change Rep. 2 211–20
McClean F, Dawson R and Kilsby C 2020 Implications of using global digital elevation models for flood risk analysis in cities Water Resour. Res. 56 e2020WR028241
Murnane R J, Daniell J E, Schaffer A M, Ward P J, Wisnemius H C, Simpson A, Tijssen A and Toro J 2017 Future scenarios for earthquake and flood risk in Eastern Europe and Central Asia Earths Future 5 693–714
Nash J E and Sutcliffe J V 1970 River flow forecasting through the use of a conceptual model Water Resour. Res. 6 282–90
Orr S, Pittcock J, Chapagain A and Dumaresq D 2012 Dams on the Mekong River: lost fish protein and the implications for land and water resources Global Environ. Change 22 925–32
Pohlschneider, Kramer A, Hull W, Blumstein S, Abdullaev I, Kuznetsova T, Strijikova E, Intermesoli E and Görlitz S 2017 Rethinking water in Central Asia: the costs of inaction and benefits of water cooperation Swiss Agency of Development and Cooperation (SDC) (Berlin Germany)
Ren Z, Su F G, Xu B Q, Xie Y and Kan B Y 2018 A coupled glacier-hydrology model and its application in Eastern Pamir J. Geophys. Res. 123 13692–713
Shaw T E, Caro A, Mendoza P, Ayala A, Pellicciotti F, Gascoin S and McPhee J 2020 The utility of optical satellite winter snow depths for initializing a glacio-hydrological model of a high-elevation, Andean Catchment Water Resour. Res. 56 e2020WR027188
Shen Y J, Shen Y, Fink M, Kralsch S and Brenning A 2018 Unraveling the hydrology of the glacialized Kaidu Basin by integrating multisource data in the Tianshan Mountains, Northwestern China Water Resour. Res. 54 557–80
Shin S, Pokhrel Y, Yamazaki D, Huang X, Torbick N, Qi J, Pattanakiat S, Ngo-Duc T and Nguyen T D 2020 High resolution modeling of River-floodplain-reservoir inundation dynamics in the Mekong River Basin Water Resour. Res. 56 e2019WR026449
Smith A, Bates P D, Wing O, Sampson C, Quinn N and Neal J 2019 New estimates of flood exposure in developing countries using high-resolution population data Nat. Commun. 10 1–7
Sun H and Su F 2020 Precipitation correction and reconstruction for streamflow simulation based on 262 rain gauges in the upper Brahmaputra of southern Tibetan Plateau J. Hydrol. 590 125484
Swain D, Wing O E, Bates P D, Done J, Johnson K and Cameron D 2020 Increased flood exposure due to climate change and population growth in the United States Earths Future 8 22020EF001778
Tanoue M, Taguchi R, Alifu H and Hirabayashi Y 2021 Residual flood damage under intensive adaptation Nat. Clim. Change 11 823–6
Tellman B, Sullivan J, Kuhn C, Kettnar A, Doyle C, Braekenridge G, Erickson T and Saylback D 2021 Satellite imaging reveals increased proportion of population exposed to floods Nature 596 80–86
Thober S, Kumar R, Wanders N, Marx A, Pan M, Rakovec O, Samaniego L, Sheffield J, Wood E F and Zink M 2018 Multi-model ensemble projections of European river floods and high flows at 1.5, 2, and 3 degrees global warming Environ. Res. Lett. 13 014003
Thurman M 2011 Natural Disaster Risks in Central Asia: A Synthesis (Bratislava: United Nations Development Programme)
Wang N, Liu W, Wang H, Sun F, Duan W, Li Z, Li Z and Chen Y 2021 Improving streamflow and flood simulations in three headwater catchments of the Tarim River based on a coupled glacier-hydrological model J. Hydrol. 603 127048
World Bank Group 2016 Europe and Central Asia Country Risk Profiles for Floods and Earthquakes (Washington, DC: World Bank)
Wu H, Adler R F, Hong Y, Tian Y and Policelli F 2012 Evaluation of global flood detection using satellite-based rainfall and a hydrologic model J. Hydrometeorol. 13 1268–84
Yamazaki D, de Almeida G A and Bates P D 2013 Improving computational efficiency in global river models by implementing the local inertial flow equation and a vector-based river network map Water Resour. Res. 49 7221–35
Yamazaki D, Kanae S, Kim H and Oki T 2011 A physically based description of floodplain inundation dynamics in a global river routing model Water Resour. Res. 47 W04501
Yan X Y, Zhang Q, Zhang W B, Ren X Y, Wang S and Zhao F N 2021 Analysis of climate characteristics in the Pan-Central-Asia arid region Arid. Zone Res. 38 1–11
Yang T, Sun F, Gentilone P, Liu W, Wang H, Yin J, Du M and Liu C 2019 Evaluation and machine learning improvement of global hydrological model-based flood simulations Environ. Res. Lett. 14 114027
Yao J, Chen Y, Chen J, Zhao Y, Tuoliewubieke D, Li J, Yang L and Mao W 2021 Intensification of extreme precipitation in arid Central Asia J. Hydrol. 598 125760
Zhang L L, Su F G, Yang D Q, Hao Z C and Tong K 2013 Discharge regime and simulation for the upstream of major rivers over Tibetan Plateau J. Geophys. Res. 118 8500–8508
Zhang Q, Gu X, Singh V P, Sun P, Chen X and Kong D 2016 Magnitude, frequency and timing of floods in the Tarim River basin, China: changes, causes and implications Glob. Planet. Change 139 44–55
Zhang Q D, Ye B S, Ding Y J, Zhang S Q, Yi S H, Wang J, Shangguan D H, Zhao C C and Han H D 2013 Coupling a glacier melt model to the variable infiltration capacity (VIC) model for hydrological modeling in north-western China Environ. Earth Sci. 68 87–101