# Hydrologic alteration and potential ecosystemic implications under a changing climate in the Chitral River, Hindukush region, Pakistan

M. Usman, X. Pan, D. Penna and B. Ahmad

## ABSTRACT

This study investigates changes in the hydrologic regime of the Chitral River, Hindukush–Karakoram–Himalayan (HKH) region, Pakistan. Different statistically based methods were used to assess climate change-induced hydrologic alterations that can possibly impact aquatic habitat in the study region. The hydrological model Hydrologiska Byråns Vattenbalansavdelning (HBV) was calibrated, validated, and applied to predict streamflow in the Chitral River basin. The HBV model was forced with the ensemble of four general circulation models under different representative concentration pathway emission scenarios to generate future streamflow under climate change conditions in the basin for the mid-twenty-first century. The results of this study show that hydrologic regimes in the study area, expressed by the magnitude, duration, frequency, timing, and rate of streamflow, are likely to alter in the future. Positive (i.e., with increased frequency) hydrologic alteration is projected for most flow parameters under all scenarios for the 2021–2050 period compared with values observed during the historical period (1976–2005). These hydrologic alterations might have impacts on fish and migratory bird species in the study area. This research can be helpful in providing practical information for more effective water resources and aquatic ecosystem management in the HKH region.

**Key words** | aquatic ecosystem, Chitral River basin, climate change, HBV, hydrological modeling, IHA, RVA

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## HIGHLIGHTS

- Investigation of changes in the hydrologic regime of the Chitral River.
- Employment of IHA and RVA methods to evaluate riverine ecosystem health.
- Hydrological modeling using HBV-light to generate future streamflow.
- Assessment of climate change impacts on different streamflow characteristics.
- Analysis of streamflow changes and their relationship with aquatic habitat.

## GRAPHICAL ABSTRACT
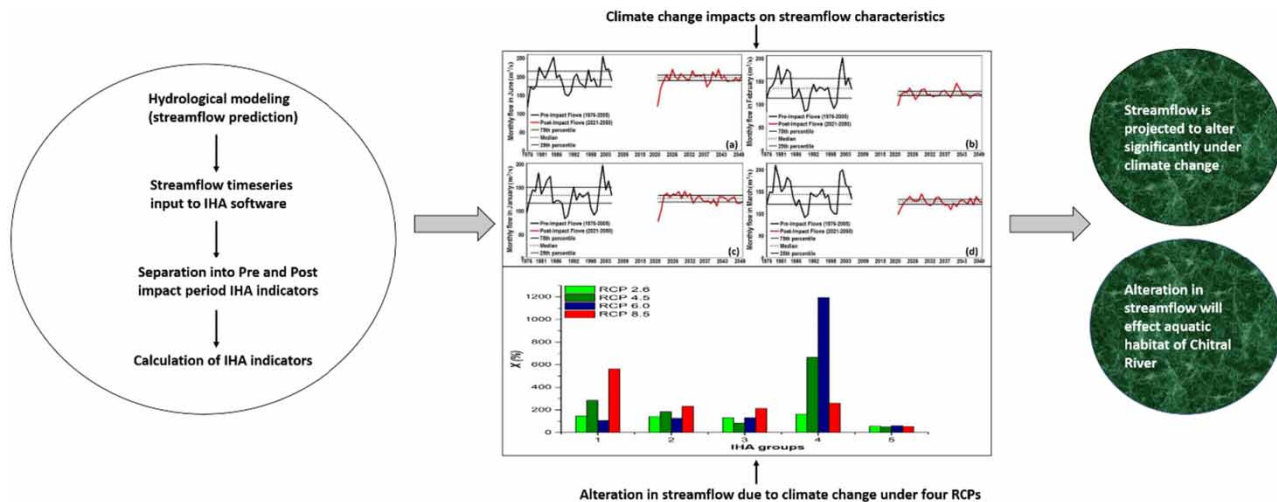


## INTRODUCTION

Climate has substantially changed compared to pre-industrial times and is projected to further alter considerably worldwide in the twenty-first century at the global scale (Hoegh-Guldberg *et al.*, 2018). Changes have also been observed in Pakistan, and extreme climatic events are predicted to increase especially in the Hindukush–Karakoram–Himalayan (HKH) region of Pakistan. The HKH region has the most overstressed aquifers in the world and is a climate change hotspot; therefore, the predicted extreme events will pose additional threats to the region, already exposed to numerous and severe flood events (Lutz *et al.* 2016). Increase in precipitation and average summer temperature is projected for catchments of the Upper Indus Basin (Archer & Fowler 2004; Fowler & Archer 2006; Bocchiola & Diolaiuti 2013; Ahmad & Hussain 2017), often associated with alterations of the hydrologic cycle (Bell *et al.* 2016). Climate change impacts are stronger in magnitude and outweigh all other direct impacts (such as dams and water withdrawals) on the water cycle (Finke *et al.* 1998; Döll & Zhang 2010). Several studies have been conducted at various spatio-temporal scales on some major rivers in the HKH region revealing significant impacts of climate change on catchment streamflow (Wijngaard *et al.* 2017; Hashmi *et al.* 2019; Li *et al.* 2019; Shrestha & Nepal 2019).

The natural flow regime of rivers is closely associated with the biodiversity and integrity of the riverine ecosystems (Poff *et al.* 1997; Petts *et al.* 2006; Roy *et al.* 2006) and it controls many physio-ecological processes (Arthington *et al.* 2006; Naiman *et al.* 2008; Guastini *et al.* 2019). These processes include the exchange of nutrients and the transport of sediments, which in turn influence factors such as velocity and depth of flow, which are critical elements of river habitats (Poff *et al.* 1997; Benda *et al.* 2004; Shiau & Wu 2007). Therefore, the flow regime of a river is important for sustaining the surrounding environment and for the functionality of aquatic, riparian, and wetland ecosystems (Poff *et al.* 1997; Petts *et al.* 2006; Roy *et al.* 2006). Alterations in flow regime can have negative impacts on stream ecosystems, including failed fish and micro-invertebrate recruitment, extinction of local species, and the successful invasion of exotic species (Bunn & Arthington 2002; Poff *et al.* 2007, 2010; Poff & Zimmerman 2010).

Fish are one of the most important constituents of biological diversity in the HKH region (Ahmed & Joyia 2003). Approximately 193 fish species have been identified in the Pakistani rivers, of which 31 species have economic importance (Rafique & Khan 2012). Eight species are widely distributed in the HKH region, including

*Oncorhynchusmykiss*, *Salmo trutta fario*, *Schizothorax pla-giostomus*, *Diptychus maculates*, *Ptychobarbus conirostris*, *Racoma labiata*, and *Schizopyge esocinus* (Rafique & Khan 2012). Flora represents another important source of biodiversity in the HKH region and plays a vital role in the catchment water cycle in terms of soil conservation and evapotranspiration fluxes. Both fish and plant biodiversity in the Chitral River are seriously exposed to ecological threats due to hydrological alteration. For instance, the Chitral River shows poor fish diversity associated with changes in water temperature and high turbidity (Rafique 2001; Bari *et al.* 2014). Moreover, deterioration of water quality in the Chitral River has been observed and is associated with physical factors depending on climate change (Nafees *et al.* 2012).

Despite the important ecological and societal implications of the climate change impacts in the Chitral River basin, previous studies so far have focused, as far as we know, only on hydrologic alterations related to changes in mean and extreme streamflow values but more detailed analysis of hydrological modifications induced by climate change and their effects on the riverine ecosystem in this region is missing and is highly needed for operational purposes. Therefore, overall, this study aims to identify and quantify the main sources of hydrologic alteration that might cause pressing effects on aquatic organisms in the Chitral River basin.

## MATERIALS AND METHODS

### Study region and data availability

The Chitral River has a drainage area of 11,396 km$^2$ and is a transboundary river basin between Pakistan and Afghanistan (Figure 1). Large parts of the basin are at high elevations and host wide glaciers. More than 50% of the catchment area is between 4,000 and 5,000 m a.s.l. (Hayat *et al.* 2019). Glacier and snowmelt waters (Burhan *et al.* 2020a) make significant flow contributions to the Chitral River and serve as a critical resource for irrigation and hydropower generation. In addition, the river water is crucial for supporting domestic activities, playing therefore a vital role in the socio-economic development of the region.

Hydrometeorological data in the Chitral River basin were available for the period 1994–2012 (Table 1). A 90-m resolution digital elevation model was also available for the study area. Potential evapotranspiration was computed using the approach by Irmak *et al.* (2003).

The results from different General Circulation Models (GCMs, Table 2) have been averaged in order to have more reliable precipitation and temperature data inputs in the study region and to carry out more solid interpretation of climate evolution and land surface-atmosphere interactions in this large-scale basin (He *et al.* 2016). As the outputs of GCMs are typically too coarse to properly represent local sub grid-scale features and dynamics (Coulibaly *et al.* 2005), they were downscaled using the statistical downscaling model suggested by Su *et al.* (2016). As GCMs do not always accurately simulate the climate variables, especially in large regions with complex topography as in our study area, biases might be present and should be corrected (Su *et al.* 2016). The bias of the GCM outputs was corrected by employing the cumulative distribution functions matching method introduced by Li *et al.* (2010) that was successfully applied in other mountain regions (Su *et al.* 2016). Data of the GCMs were forced with four respective representative concentration pathways (RCPs), a set of scenarios that include time series of emissions and concentrations of greenhouse gases and aerosols and chemically active gases, as well as land use/land cover (Van Vuuren *et al.* 2011). The RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5 emission scenarios were adopted: the RCP 2.6 represents a low emission scenario, with a radiative forcing of 2.6 w/m$^2$ towards the end of the twenty-first century, the RCP 4.5 is an intermediate (average) emission scenario with a radiative forcing of 4.5 w/m$^2$ towards the end of the century, the RCP 6.0 represents a high emission scenario with radiative forcing of 6.0 w/m$^2$ towards the end of the century, and the RCP 8.5 corresponds to the highest (extreme) emission scenario, with a radiative forcing of 8.5 w/m$^2$ towards the end of the century (Van Vuuren *et al.* 2011).

### Hydrological modelling

The HBV-light model was used to simulate daily streamflow in the Chitral River basin. HBV-light is a modified version of HBV (Seibert & Vis 2012), a lumped, conceptual, and
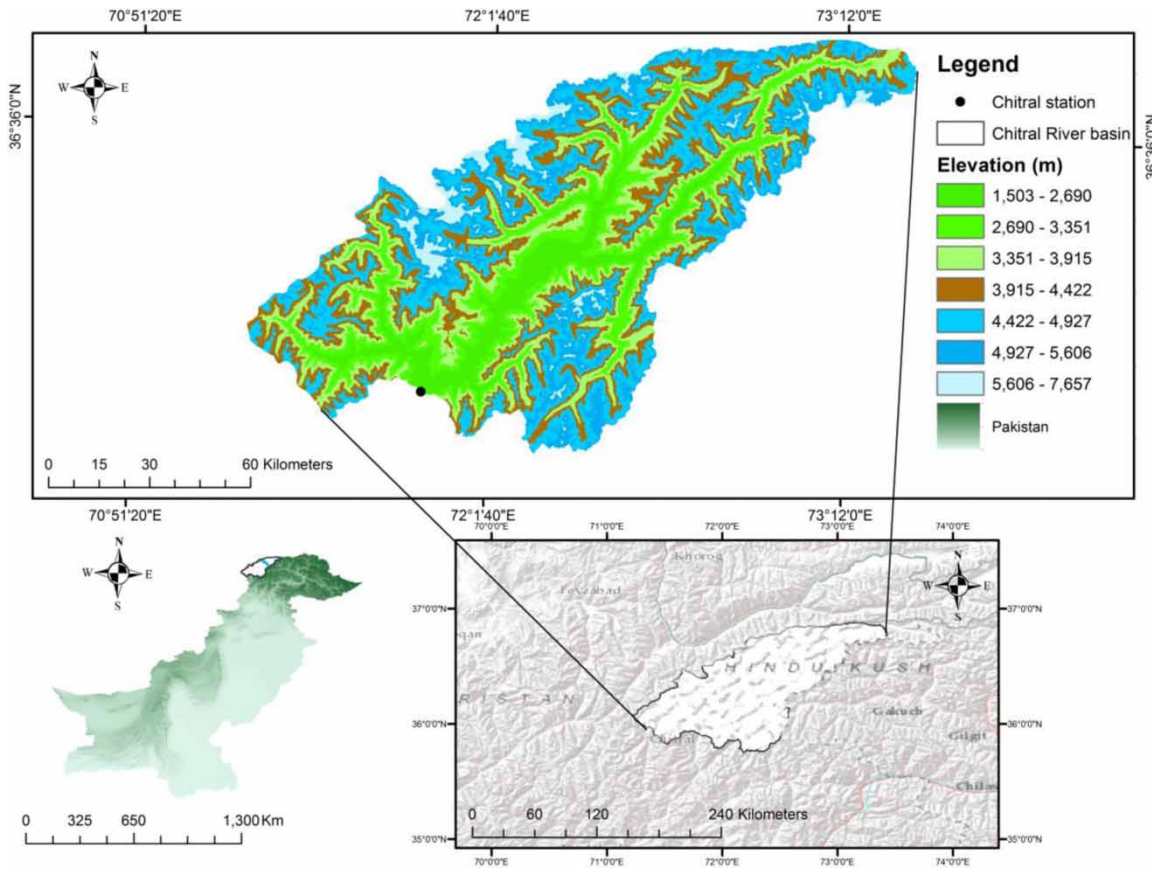
**Figure 1** │ Location and elevation map of the Chitral River basin.

**Table 1** │ Hydrometeorological and topographic data available for the Chitral River basin

| Stations and elevation models | Variable | Temporal resolution | Time period | Source agency/department |
|---|---|---|---|---|
| Chitral meteorological station | Precipitation, minimum temperature, maximum temperature | Daily | 1994–2012 | Pakistan Meteorological Department, Pakistan |
| Chitral hydrological station | Streamflow | Daily | 1994–2012 | Surface Water Hydrology Project, Water and Power Development Authority, Pakistan |
| Digital Elevation Model | 90 m resolution | | | Shuttle Radar Topographic Mission, https://doi.org/10.5067/MEaSUREs/SRTM/SRTMGL3.003 |

semi-distributed hydrological model developed by the Swedish Meteorological and Hydrological Institute. The modified version is based on the degree-day method to simulate snowmelt based on a linear function of the temperature difference between average air temperature and the threshold temperature for snowmelt and is well suited to describe the runoff variability (Seibert 2001;

Radchenko *et al.* 2013; Bhattarai *et al.* 2018; Usman *et al.* 2019; Burhan *et al.* 2020b). The model has different routines: snow routine, soil routine, response routine, and routing routine. The time series of temperature, precipitation, and potential evaporation were used as inputs to the model to simulate streamflow, as follows: in the snow routine, precipitation was first utilized as input and then simulated by the

**Table 2** │ Description of the general circulation models (GCMs) used in this study.

| ID | Model name | Modelling group | Country | Variables | Time period | Temporal scale |
|---|---|---|---|---|---|---|
| 1 | GFDL-ESM2M | NOAA Geophysical Fluid Dynamics Laboratory | United States of America | | | |
| 2 | IPSL-CM5A-LR | Institute Pierre-Simon Laplace | France | | | |
| 3 | MIROC-ESM-CHEM | Atmospheric and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology | Japan | Precipitation, minimum temperature, maximum temperature | 2021–2050 | Daily |
| 4 | NorESM1-M | Bjerknes Centre for Climate Research, Norwegian Climate Centre | Norway | | | |

model either as snow or rain depending on a threshold temperature. In the soil routine, the simulation of groundwater recharge and actual evaporation depended on the actual water storage. Actual soil evaporation matched potential evaporation when the availability of water was not limiting evaporation. When water availability limited evaporation, a linear reduction was utilized. In the response, routine streamflow was calculated as a function of water storage. Finally, in the routing routine, a triangular weighting function was employed for the purpose of simulating the route of the streamflow at the basin outlet. For a comprehensive description of the model including all the associated characteristics and some applications, the reader is referred to the following studies (Bergström 1976; Seibert 2005; Seibert & Vis 2012; Bhattarai *et al.* 2018; Usman *et al.* 2019).

## Model development and performance assessment

The HBV model was calibrated by employing an automatic calibration method, i.e., the genetic algorithm and Powell optimization method (Seibert 2000). This method is based on a recombination of parameter sets and the best set of parameters resulting in the highest objective function (e.g. Nash–Sutcliffe Efficiency index (NSE)) was selected. This process was repeated several times to obtain the best-optimized set of parameters and improve the model efficiency. Calibration was performed by dividing the available daily time series (1994–2012) into two periods. The first period (1994–2007) was used for calibration of the model, using the first years as the warm-up period. The calibrated model

was then validated against the different observed data from the second period (2008–2012). The model was applied for the generation of future streamflow using the average weather data obtained by the four GCMs forced with the different RCPs.

Different measures to assess the model efficiency during the model calibration and validation were employed. They include the NSE (Nash & Sutcliffe 1970), the coefficient of determination ($R^2$), and the percent bias (PBIAS) (Moriasi *et al.* 2007), the index of agreement measure (IoAd) (Willmot 1982), and volumetric efficiency (VE) (Criss & Winston 2008). The NSE, $R^2$, IoAd, and VE metrics have perfect values of unity, and PBIAS has an optimum value of 0. The five efficiency measures were computed as follows:

$$\text{NSE} = 1 - \frac{\sum (Q_{\text{obs}} - Q_{\text{sim}})^2}{(Q_{\text{obs}} - \overline{Q_{\text{sim}}})^2} \tag{1}$$

$$R^2 = \frac{\left(\sum (Q_{\text{obs}} - \overline{Q_{\text{obs}}})^2 (Q_{\text{sim}} - \overline{Q_{\text{sim}}})^2\right)^2}{\sum (Q_{\text{obs}} - Q_{\text{obs}})^2 \sum (Q_{\text{sim}} - Q_{\text{sim}})^2} \tag{2}$$

$$\text{PBIAS} = \frac{\sum_{w=1}^{t} (Q_{\text{obs}} - Q_{\text{sim}})}{\sum_{w=1}^{t} (Q_{\text{obs}})} * 100 \tag{3}$$

$$\text{IoAd} = 1 - \frac{\sum_{t=1}^{z} (Q_{\text{obs}} - Q_{\text{sim}})^2}{\sum_{t=1}^{z} (|Q_{\text{obs}} - \overline{Q_{\text{obs}}}| + |Q_{\text{sim}} - Q_{\text{sim}}|)^2} \tag{4}$$

$$\text{VE} = 1 - \frac{\sum_{t=1}^{z} |Q_{\text{obs}} - Q_{\text{sim}}|}{\sum_{t=1}^{z} Q_{\text{obs}}} \tag{5}$$

where $t$ is the total number of time steps, and $w$ is the time-step, $Q_{obs}$ is the observed streamflow value and $Q_{sim}$ is the model simulated (predicted) streamflow value.

## Analysis of streamflow alteration

Potential streamflow alterations caused by changing climate conditions in the study basin were first assessed using the indicators of hydrologic alteration (IHA) method (Richter *et al.* 1996). The IHA method includes 33 parameters that determine how flow regime is perturbed by different disturbances (Table S1 in Supplementary Materials). Out of 33 IHA indicators, one indicator (number of zero-flow days) was not considered in this study, as no zero-flow days were found in the monitoring period. The remaining 32 parameters were distributed in five different groups based on magnitude, timing, frequency, duration, and rate of change of streamflow. The five groups were defined as follows.

Group 1 includes parameters related to the magnitude of water condition (monthly mean flows); group 2 includes parameters representing the magnitude and duration of annual extreme flows; group 3 includes parameters describing the frequency of occurrence of drought or flood conditions; group 4 includes parameters representing the frequency and duration of high and low pulses (defined as the annual periods when the daily flows are above the 75th percentile and below the 25th percentile of daily streamflow); and group 5 includes parameters related to the rate of change in water flow.

The computation of the different indices involves four steps: (1) definition of the streamflow data series for pre-impact (1976–2005) and post-impact (2021–2050) periods; (2) calculation of hydrologic attributes for the entire monitoring period (1976–2050); (3) computation of inter-annual statistics (central tendency and dispersion measure); (4) comparison of pre-impact and post-impact period streamflow data and calculation of the percent change for each of the IHA parameters (3rd column in Table S1). Thirty years were selected as the pre-impact period and an additional 30 years were used as the post-impact period; these values were chosen based on the recommendation that at least 20 years should be used to account for natural climatic variability (Richter *et al.* 1997; Pfeiffer & Ionita 2017).

The second approach adopted to assess climate change effects on hydrologic regimes was the range of variability approach (RVA). This method identifies annual river management targets which are based on statistical characterization of the parameters of the IHA (Shiau & Wu 2008; Zolezzi *et al.* 2009; Jiang *et al.* 2014; Xue *et al.* 2017; Vu *et al.* 2019). The RVA uses the pre-impact natural streamflow conditions of the IHA parameter values as a reference for determining the degree of alteration of natural flow regimes, setting a target range for each hydrologic parameter. In this study, the target for the assessment of the hydrologic alteration was chosen as the percent change between the 25th and 75th percentile of the pre-impact parameter values. The rationale for this choice is based on the fact that if there are no distinct effects of climate change, the post-impact values should occur with similar frequency as the natural or pre-impact baseline streamflow regimes. This study followed the approach of the hydrologic alteration proposed by Richter *et al.* (1998) and the improved overall degree of the hydrologic alteration proposed by Xue *et al.* (2017) that classifies hydrologic alteration ($X$) into five classes: slight alteration ($X < 20\%$); low alteration ($20\% < X < 40\%$); moderate alteration ($40\% < X < 60\%$); high alteration ($60\% < X < 80\%$); and severe or extreme alteration ($X > 80\%$). The degree of hydrological alteration (HA) of each parameter was then calculated as follows (Richter *et al.* 1998):

$$HA = \frac{(obs - exp)}{exp} * 100 \qquad (6)$$

where HA is the degree of hydrologic alteration, obs is the number of years in which the observed parameter value fell within the target range, and exp indicates the number of years in which the value of the parameter is expected to fall within the target range. $X$ is calculated using Equation (5) (Xue *et al.* 2017)

$$X = \sqrt{\frac{HA_{max}^2 + HA_{avg}^2}{2}} \qquad (7)$$

where $X$ is the improved degree of hydrologic alteration, and $HA_{max}$ and $HA_{avg}$ are the maximum and average values for each group of the IHA indicators, respectively.

The degree to which the RVA target ranges are not attained is accepted as a measure of hydrologic alteration. A positive HA value indicates that the respective parameter values fell within the target range more frequently in the post-impact period than expected, and a negative HA value indicates that the respective parameter values fell within the target range less frequently in the post-impact period than expected. A hydrologic alteration is zero when the observed frequency of post-impact annual values that fall within the RVA target range equals the expected frequency.

The HBV-light, IHA software version 7.1 (The Nature Conservancy 2009), Microsoft Excel, and OriginPro have been used for generating the models and the statistical analysis.

## RESULTS AND DISCUSSION

### Calibration and validation

The time series during the model calibration and validation periods and the metrics of model of performance (Figures 2 and 3 and Table 3) indicate a good agreement between the observed and the simulated daily streamflow values, which means the HBV-light performed well both during calibration and validation. The NSE values greater than 0.9 during the calibration and greater than 0.8 during the validation were achieved. The $R^2$ value was above 0.9 for both calibration

and validation, PBIAS was 3.7 and −2.0% for the calibration and validation period, IoAd was more than 0.95 for both calibration and validation, and VE was 0.81 for calibration and 0.77 for validation, respectively. All these observations reveal that the HBV model was efficient in replicating catchment processes in the Chitral River basin with very small prediction uncertainties. However, the PBIAS values indicate that the model slightly underestimated streamflow during the calibration and overestimated streamflow during the validation period (Figure 3).

### Measure of hydrological alteration and ecological implications

All 32 ecologically relevant (IHA) parameters adequately represented the streamflow. Changes in streamflow parameters projected in future periods by the model indicate climate change impacts on streamflow, with different extents and implications according to the different IHA groups.

### Alteration of monthly streamflow

The HA values of the 12 parameters of the IHA group 1 (monthly streamflow) for the Chitral River under the RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5 emission scenarios are listed in Table S2. Ten out of 12 parameters of group 1 returned high HA values (HA > 67%), with especially high values for June, January, and November under the RCP
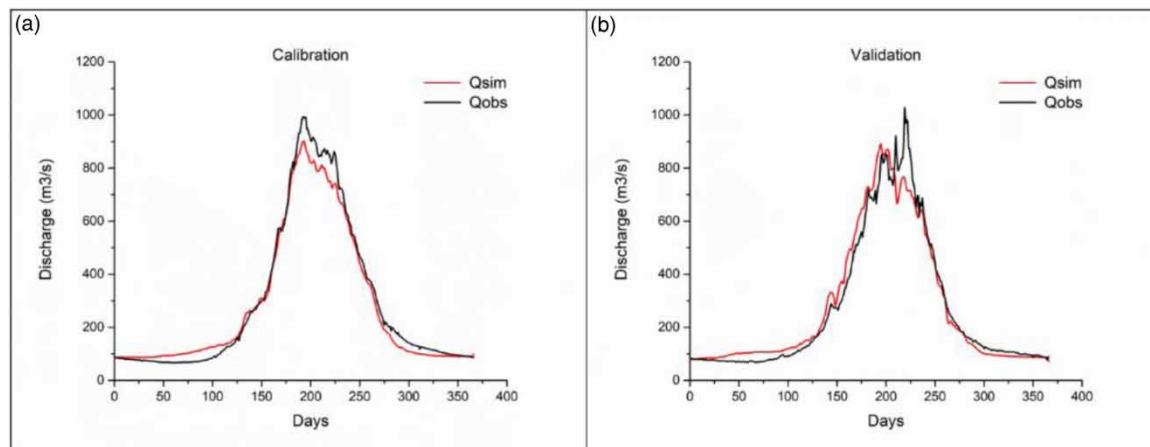


**Figure 2** | Mean daily streamflow of Chitral River: (a) Calibration (1994–2007), (b) validation (2008–2012) of HBV model.
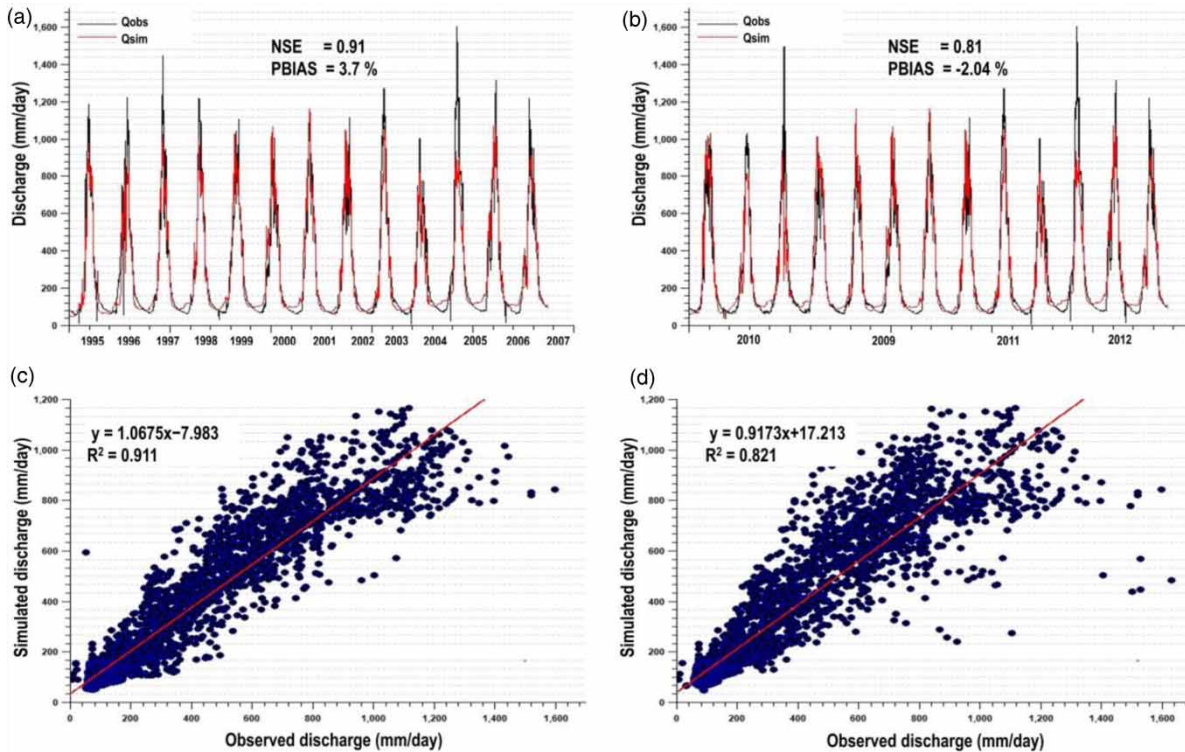
**Figure 3** │ Calibration (1995–2007, (a)) and validation (2009–2012, (b)) of the HBV model for the Chitral River basin at daily scale Scatter plots depicting fit of the observed and simulated values for the calibration (c) and validation (d) period.

**Table 3** │ The results of metrics used to evaluate HBV efficiency

**Efficiency evaluation metrics**

|            | NSE  | R²   | PBIAS | IoAd | VE   |
|------------|------|------|-------|------|------|
| Calibration | 0.91 | 0.91 | 3.7%  | 0.97 | 0.81 |
| Validation  | 0.81 | 0.82 | −2.0% | 0.95 | 0.77 |

2.6 emission scenario. Under the RCP 4.5 and 6.0 emission scenarios, nine and six parameters, respectively, of group 1 returned high values (HA > 67%). Under the extreme emission scenario, eight parameters of group 1 returned high HA values. The maximum HA values of group 1 under each emission scenario are given in Figure 4.

The IHA group 1 is composed of parameters related to the magnitude of monthly streamflow and representing seasonal variations. Most of the parameters of group 1 projected a significant high value of HA, revealing an increased frequency of high flows in the post-impact period compared to the pre-impact period under all

emissions scenarios. From mid-spring to early autumn, snow and glacier melt are major contributors to streamflow in the Chitral River basin (Hasson 2016). However, in the dry season (October to February), most of the streamflow is composed of groundwater, and liquid precipitation does not contribute significantly to streamflow. This increase in HA values implies that the frequency of these parameters has increased in the post-impact period compared to that in the pre-impact period. Generally, most of the parameters of group 1 indicate an increased frequency of streamflow alteration in the post-impact period compared to the pre-impact period under all emissions scenarios. However, this increase in frequency is more significant in winter, early spring, and early summer in the post-impact period compared to the pre-impact period under all emissions scenarios, suggesting that more values are likely to fall within the target range in the future during these seasons (Figure 4). Furthermore, the magnitude of this increase in frequency is much stronger under the RCP 8.5 emissions scenario, indicating that extreme emissions might be
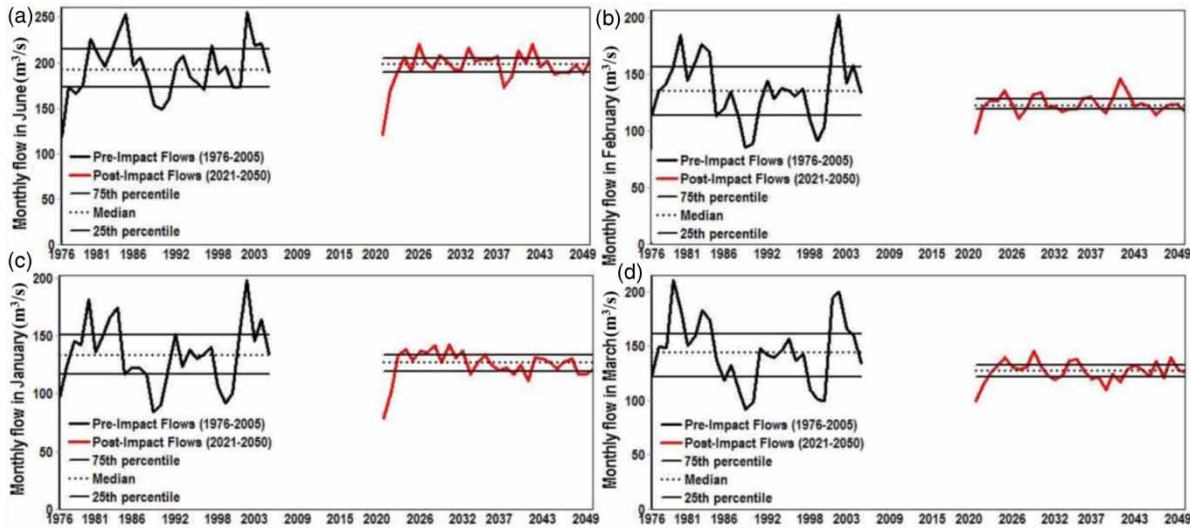
**Figure 4** │ Parameters of IHA group 1 showing maximum HA under each emission scenario: (a) monthly flow in June, RCP 2.6, (b) monthly flow in February for RCP 4.5; (c) monthly flow in January for RCP 6.0; and (d) monthly flow in March for RCP 8.5.

suitable for attaining the targeted range. According to the improved overall degree of hydrologic alteration, the parameters of group 1 (monthly median flows) are likely to be altered most under the extreme emission scenario and least under the high emission scenario.

The most abundant species of fish in the Chitral River (*Schizothorax plagiostomus*) spawns twice a year from March to April and from September to October (Qadri *et al.* 1982; Jan *et al.* 2014). Therefore, significant hydrologic alteration in monthly streamflow (increase frequency of high streamflow values especially in winter) projected for these months potentially affects spawning of these fish species.

### Alteration of annual extreme flows

The HA values of the 12 parameters of the IHA group 2 (annual extreme flow conditions) and the two parameters of the IHA group 3 (annual extreme flow conditions) for the Chitral River under the RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5 emissions scenarios are listed in Table S3. Ten out of 15 parameters of the IHA groups 2 and 3 returned high HA values (>67%), with the highest values under the RCP 2.6 emission scenario. The number of parameters that returned high HA values (>67%), under RCP 4.5 emissions scenario was 40% less than that of the low emissions scenario. Under RCP 6.0 and RCP 8.5 emissions

scenarios, seven parameters returned high HA values. The maximum HA values for parameters of groups 2 and 3 under each emissions scenario are given in Figures 5 and 6.

According to the improved overall degree of hydrologic alteration, parameters of group 2 (magnitude and duration of annual extreme flows) are likely to be altered most under extreme emissions scenario and least under average emissions scenario.

There are two parameters in the IHA group 3 (timing of annual extreme flows), namely, the date of minimum flow and the date of maximum flow. The date of minimum flow is the only parameter that projected on average negative low HA values (<-27%), but this change is not significant compared to other changes (average positive HA values >194%). On the contrary, the date of maximum flow projected an enormous increase in its frequencies in the post-impact period compared to the pre-impact period, indicating that it is more likely to lie within the targeted range in the future. The change in flow timings can impair ecosystem functioning (Baron *et al.* 2002) by effecting fish migration and spawning, as well as egg hatching, rearing, movement onto the floodplains for feeding and reproduction, and migration upstream and downstream (Poff *et al.* 1997; Gao *et al.* 2018). If the water level reaches too low or too high values during spawning or reproduction months, it can affect the propagation of fish species and likely of other
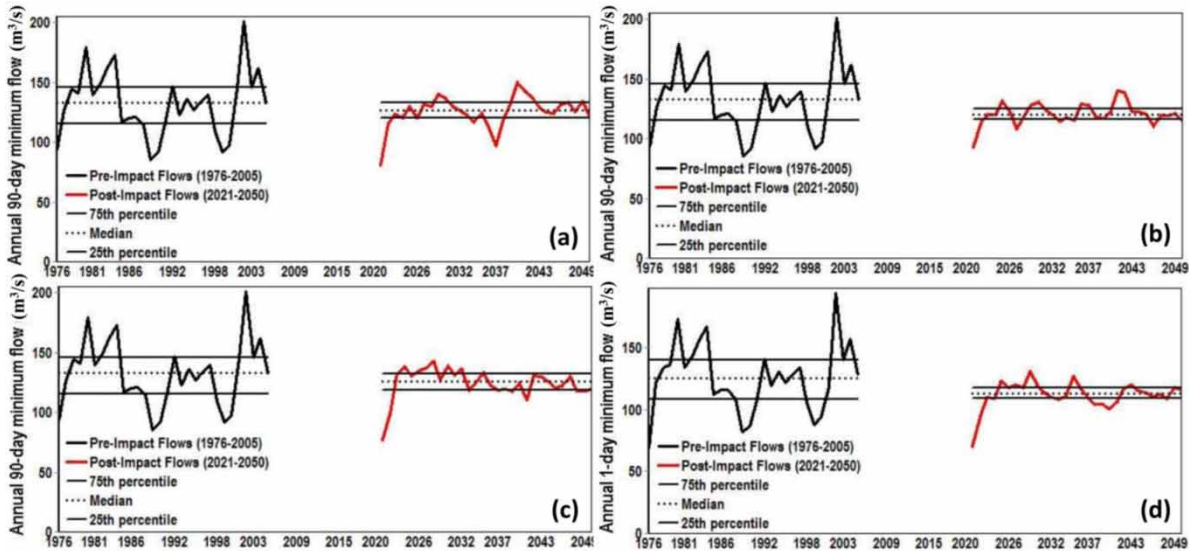
**Figure 5** | Parameters of IHA group 2 showing maximum HA under each emission scenario: (a) Annual 90-day minimum flow parameter under RCP 2.6, (b) annual 90-day minimum flow parameter under RCP 4.5, (c) annual 90-day minimum flow parameter under RCP 6.0, and (d) annual 1-day minimum flow parameter under RCP 8.5.
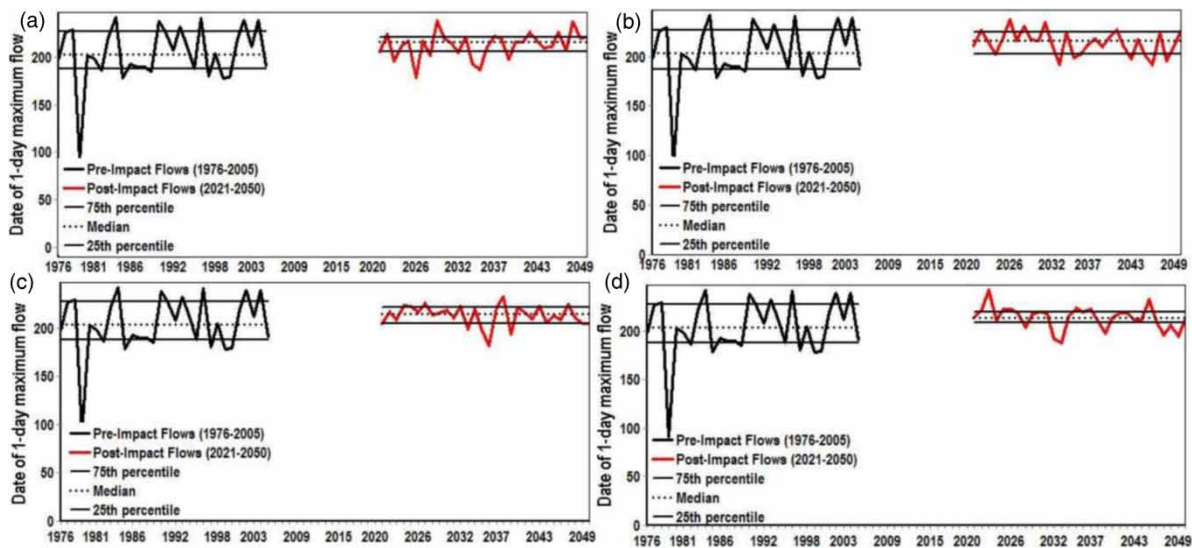


**Figure 6** | Parameters of IHA group 3 showing maximum HA under each emission scenario: (a) Date of 1-day maximum flow parameter under RCP 2.6, (b) date of 1-day maximum flow parameter under RCP 4.5, (c) date of 1-day maximum flow parameter under RCP 6.0, and (d) date of 1-day maximum flow parameter under RCP 8.5.

aquatic organisms. Moreover, most of the birds enter and exit Pakistan through the Chitral River, which makes its ecosystem more vulnerable to changes in flow timing, and the projected significant increase in the date of maximum flow might have an impact on the natural routes of different migratory species. These results depict an increase in the frequency of parameters that are relevant to low flows in the

post-impact period compared to the pre-impact period under all emissions scenarios; additionally, the results indicate that the quantity of parameters undergoing HA of high (positive) category is reduced as radiative forcing in climate increases. However, the magnitude of change in the low flow indicators strengthens under the extreme emissions scenarios.

## Alteration of magnitude, frequency, and duration of annual extreme flows and flow changes

The HA values of the four parameters of group 4 (frequency and duration) and the three parameters of group 5 (frequency and duration) for the Chitral River, under all RCPs, are listed in Table S4. Four of the seven parameters in groups 4 and 5 under the RCP 2.6 emission scenario have very high HA values (>67%). Four parameters

returned high HA values also for the RCP 4.5 emissions scenario, although the magnitude of change is much stronger here than for RCP 2.6. For RCPs 6.0 and 8.5, five and three parameters returned high values, respectively. The maximum HA values of groups 4 and 5 under each emissions scenario are given in Figures 7 and 8.

Most of the parameters in the IHA group 4 (frequency and duration) have positive projected HA values. An HA of up to 200% in low-pulse counts under the RCP 8.5
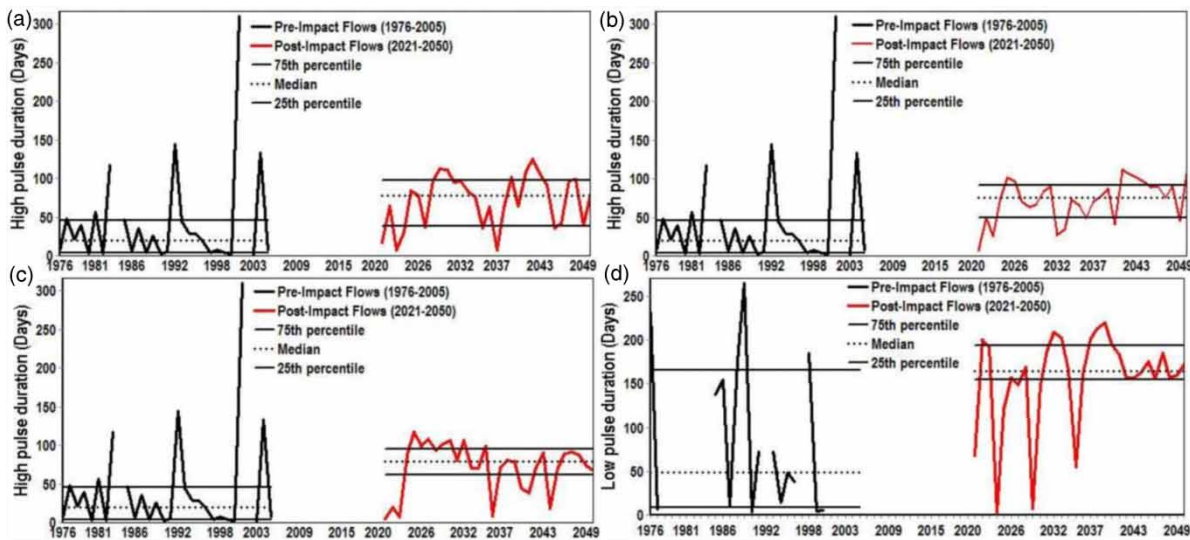


**Figure 7** │ Parameters of IHA group 4 showing maximum HA under each emission scenario: (a) high-pulse duration flow parameter under RCP 2.6, (b) high-pulse duration flow parameter under RCP 4.5, (c) high-pulse duration flow parameter under RCP 6.0, and (d) low-pulse duration flow parameter under RCP 8.5.
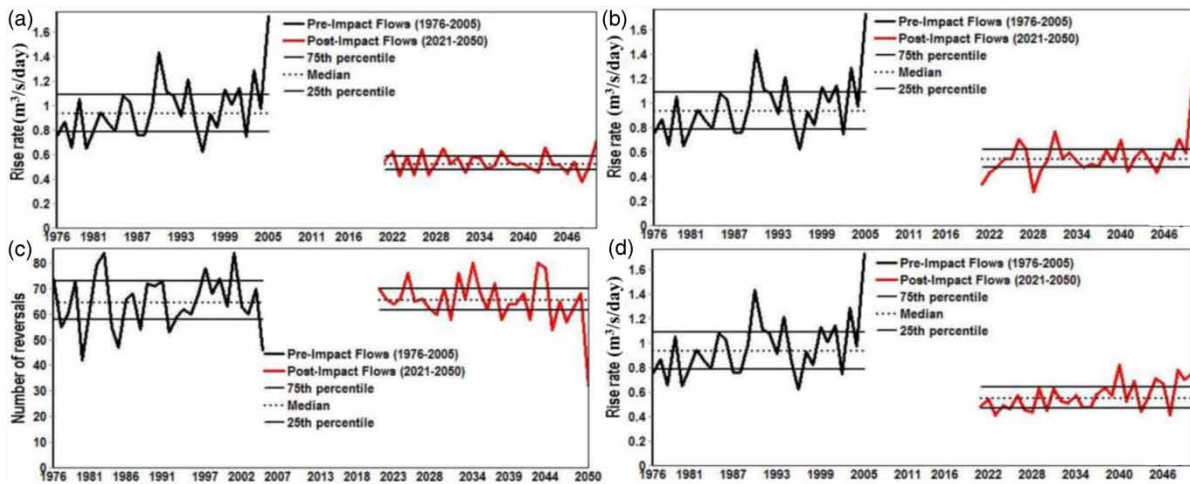


**Figure 8** │ Parameters of IHA group 5 showing maximum HA under each emission scenario: (a) rise rate flow parameter under RCP 2.6, (b) rise rate flow parameter under RCP 4.5, (c) number of reversals flow parameter under RCP 6.0, and (d) rise rate flow parameter under RCP 8.5.

emission scenario is likely to considerably alter the ecological environment of the Chitral River floodplain by foisting basic restrictions on the aquatic communities, and it may significantly affect the population and diversity of fish species and other organisms.

## Hydrologic alteration of all parameters for the four RCPs

The ranked HA values of all 32 parameters of the five groups for the RCP 2.6, 4.5, 6.0, and 8.5 emissions scenarios are illustrated in Table S5. The maximum HA was projected for the monthly streamflow indicator in June of group 1, and the minimum HA was projected for the date of the minimum streamflow parameter of the third IHA group for the RCP 2.6 emission scenario. Under the RCP 4.5 emission scenario, the maximum HA was projected for high-pulse durations and minimum HA was projected for the date of the minimum streamflow parameter of group 3. High-pulse duration experienced the maximum HA and parameter date of the minimum streamflow was the least hydrologically altered parameter for the RCP 6.0 emissions scenario. These results indicate that the days in the year when the minimum streamflow was observed will likely be similar in the future to those in the past, under different emissions scenarios.

The fall rate of streamflow (the rate of change of flow, group 5) remained unchanged in the post-impact period under all respective emissions scenarios. The number of reversals flow parameters (transitions between positive and negative streamflow, i.e., the instants when streamflow values start to vary from high to low values (fall rate) and from low to high values (rise rate)) projected a high increase in the post-impact period compared to the pre-impact period under the RCP 6.0 emissions scenario, which is an indicator of enhanced frequency in alternating periods (Pfeiffer & Ionita 2017). An increase in the number of reversals under the high emissions scenario suggests that climate change is likely to result in the modification of streamflow characteristics, e.g., high flow variability, of the Chitral River. It is interesting to note that nearly 60% of parameters in the IHA groups 4 and 5 projected a significant increase in their frequency in the post-impact period compared to the pre-impact period, and the average to high emissions scenarios projected stronger magnitudes of change.

## Improved overall degree of hydrologic alteration

The improved overall degree of hydrologic alteration ($X$) for the five IHA groups and the four RCPs is reported in Figure 9, calculated using Equation (5). The highest overall $X$ values were projected for group 4 (magnitude, frequency, and duration of annual extreme flows) for RCPs 6.0 and 4.5, followed by the first group for RCP 8.5. Consistently lower values were observed for group 5 for all RCPs. Groups 2 and 3 showed relatively similar $X$ values.

Fourteen, 18, 9, and 16 parameters out of 32 indicators returned HA values of more than 100% in the post-impact period for the low (RCP 2.6), average (RCP 4.5), high (RCP 6.0), and extreme (RCP 8.5) emission scenarios, respectively. The maximum average alteration (323%) was returned for the RCP 6.0 emission scenario and the minimum average alteration (127%) was projected for the RCP 2.6 emission scenario in all IHA groups (Table S6).

## CONCLUDING REMARKS

In this study, an assessment of hydrological alteration was performed in the flow regime of the Chitral River in the HKH region, Pakistan. The widely used methods of the IHA and the non-parametric RVA were adopted to characterize the degree of alteration and the possible future
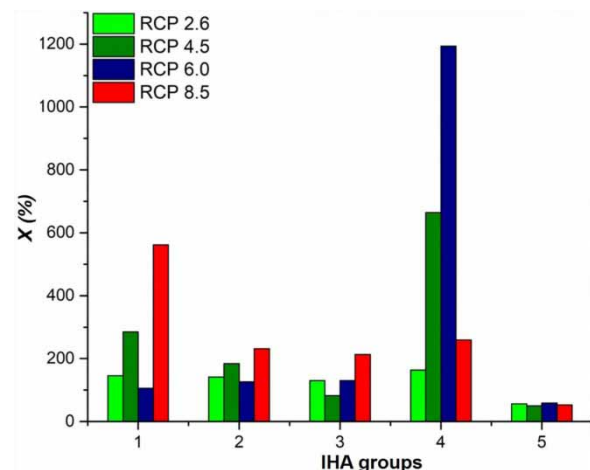


**Figure 9** │ Improved overall degree of hydrologic alteration ($X$), of the five IHA groups.

impacts on the riverine (ecohydrological) system under different future climatic conditions. The HBV-light hydrological model employed in this study showed a good streamflow prediction efficiency. The average results from climatic multi-model ensemble projections in this large basin are used to feed the HBV-light and predict future streamflow regimes more reliably.

The IHA/RVA analysis reflected a range of streamflow characteristics. Natural streamflow conditions were projected to change in the mid-twenty-first century. Our results suggest an increase in the alterations of all five IHA groups, representing the magnitude, duration, frequency, timing of daily streamflow, and the rate of change of streamflow. These alterations might have impacts on the most abundant fish species in the Chitral River, especially during their spawning and development stages, as well as on the migration processes of migratory bird species that are common in the study area.

Different previous studies (e.g., Finke *et al.* 1998; Döll & Zhang 2010; Chen *et al.* 2019) revealed that the impacts of climate change are stronger in magnitude and outweigh all other direct impacts on the streamflow (e.g., those related to unsustainable use of surface water) and need to be adequately considered in planning and management of water resources (Serrat-Capdevila *et al.* 2007). However, it might be difficult to explicitly identify the individual impacts of climate change on hydrologic alteration (Malmqvist & Rundle 2002; Pfeiffer & Ionita 2017) and this limitation applies also to this study. Despite this limitation, the work adequately describes the overall streamflow regime alteration due to climate change in the Chitral River basin, offering potentially useful information to different stakeholders responsible for policy and decision making for defining the vulnerability of aquatic ecosystems to hydrologic alteration and for more effective and sustainable water resources and aquatic ecosystem management. This study improves our knowledge and understanding of the relationship among aquatic habitat, streamflow alteration, and climate change, and can provide references for further studies in this region. More research on the quantification of climate change impacts is necessary, possibly adopting more integrated approaches that consider the combined effect of multiple sources of alteration on river streamflow.

## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

## REFERENCES

Ahmad, B. & Hussain, A. 2017 Evaluation of past and projected climate change in Pakistan region based on GCM20 and RegCM4. 3 outputs. *Pakistan Journal of Meteorology* 13 (26), 63–86. Available from: http://www.pmd.gov.pk/rnd/ rndweb/rnd_new/journal/vol13_issue26_files/6_ Evaluation_of_Pastand_Projected_Climate_Change_in_ Pakistan_Region_Based_on_GCM20_And_RegCM4. 3_Outputs.pdf.

Ahmed, S. & Joyia, M. F. 2003 *Northern Areas Strategy for Sustainable Development*. International Union for Conservation of Nature and Natural Resources, Background Paper: Water – Pakistan, Northern Areas Programme, p. 67. Available from: https://portals.iucn.org/library/node/8455

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. Available from: https://www.hydrol-earth-syst-sci.net/8/47/2004/.

Arthington, A. H., Bunn, S. E., Poff, N. L. & Naiman, R. J. 2006 The challenge of providing environmental flow rules to sustain river ecosystems. *Ecological Applications* 16 (4), 1311–1318. https://doi.org/10.1890/1051-0761(2006) 016[1311:TCOPEF]2.0.CO;2.

Bari, F., Yousafzai, A. & Shah, S. 2014 Similarity in ichthyodiversity of two connected rivers in Pak–Afghan border: River Chitral and River Bashgal and their frequency of distribution. *Journal of Biodiversity and Environmental Sciences* 5, 2220–6663. Available from: https://www. semanticscholar.org/paper/Similarity-in-ichthyodiversity-of-two-connected-in-Bari-Yousafzai/ c3e76488b1a0162f5b8b718386f6674aa6c9d504.

Baron, J. S., Poff, N. L., Angermeier, P. L., Dahm, C. N., Gleick, P. H., Hairston Jr., N. G., Jackson, R. B., Johnston, C. A., Richter, B. D. & Steinman, A. D. 2002 Meeting ecological and societal needs for freshwater. *Ecological Applications* **12** (5), 1247–1260. https://doi.org/10.1890/1051-761(2002) 012[1247:MEASNF]2.0.CO;2

Bell, V. A., Kay, A. L., Davies, H. N. & Jones, R. G. 2016 An assessment of the possible impacts of climate change on snow and peak river flows across Britain. *Climatic Change* **136** (3–4), 539–553. Available from: https://link.springer. com/article/10.1007/s10584-016-1637-x.

Benda, L. E. E., Poff, N. L., Miller, D., Dunne, T., Reeves, G., Pess, G. & Pollock, M. 2004 The network dynamics hypothesis: how channel networks structure riverine habitats. *BioScience* **54** (5), 413–427. https://doi.org/10.1641/0006-3568(2004) 054[0413:TNDHHC]2.0.CO;2.

Bergström, S. 1976 *Development and Application of A Conceptual Runoff Model for Scandinavian Catchments.* Lund Institute of Technology, University of Lund, Norrköping, p. 134.

Bhattarai, S., Zhou, Y., Shakya, N. M. & Zhao, C. 2018 Hydrological modelling and climate change impact assessment using HBV light model: a case study of Narayani River Basin, Nepal. *Nature Environment and Pollution Technology* **17** (3), 691–702. Available from: http://www. neptjournal.com/upload-images/NL-65-5-(3)D-698.pdf.

Bocchiola, D. & Diolaiuti, G. 2013 Recent (1980–2009) evidence of climate change in the upper Karakoram, Pakistan. *Theoretical and Applied Climatology* **113** (3–4), 611–641. Available from: https://link.springer.com/article/10.1007/ s00704-012-0803-y.

Bunn, S. E. & Arthington, A. H. 2002 Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management* **30** (4), 492–507. https://doi.org/10.1007/s00267-002-2737-0.

Burhan, A., Usman, M., Bukhari, S. A. A. & Sajjad, H. 2020a Contribution of glacier, snow and rain components in flow regime projected with HBV under AR5 based climate change scenarios over Chitral river basin (Hindukush Ranges, Pakistan). *International Journal of Climate Research* **4** (1), 24–36.

Burhan, A. K., Usman, M., Bukhari, S. A. A., Khan, M. T. & Malik, K. 2020b Prognosis of hydro-meteorological attributes based on simulation and projection of streamflow in a high-altitude basin using Hydrologiska Byråns Vattenbalansavdelning (HBV) model. *Aquademia* **4** (1), ep20015.

Chen, Q., Chen, H., Wang, J., Zhao, Y., Chen, J. & Xu, C. 2019 Impacts of climate change and land-use change on hydrological extremes in the Jinsha River Basin. *Water* **11** (7), 1398. Available from: https://www.mdpi.com/2073-4441/11/7/1398.

Coulibaly, P., Dibike, Y. B. & Anctil, F. 2005 Downscaling precipitation and temperature with temporal neural networks. *Journal of Hydrometeorology* **6** (4), 483–496. https://doi.org/10.1175/JHM409.1.

Criss, R. E. & Winston, W. E. 2008 Do Nash values have value? Discussion and alternate proposals. *Hydrological Processes* **22**, 2723–2725. https://doi.org/10.1016/j.jhydrol.2009.08.003.

Döll, P. & Zhang, J. 2010 Impact of climate change on freshwater ecosystems: a global-scale analysis of ecologically relevant river flow alterations. *Hydrology & Earth System Sciences Discussions* **7** (1). https://doi.org/10.5194/hess-14-783-2010

Finke, W., Fröhlich, W., Haberkorn, R., Krause, S., Lauschke, C. & Oppermann, R. 1998 *Untersuchungen Zum Abflussregime der Elbe; BfG-1228.* Bundesanstalt für Gewässerkunde, Koblenz/Berlin.

Fowler, H. J. & Archer, D. R. 2006 Conflicting signals of climatic change in the Upper Indus Basin. *Journal of Climate* **19** (17), 4276–4293. https://doi.org/10.1175/JCLI3860.1.

Gao, B., Yang, D., Qin, Y., Wang, Y., Li, H., Zhang, Y. & Zhang, T. 2018 Change in frozen soils and its effect on regional hydrology, upper Heihe basin, northeastern Qinghai-Tibetan Plateau. *Cryosphere* **12** (2). https://doi.org/10.5194/tc-12-657-2018.

Guastini, E., Zuecco, G., Errico, A., Castelli, G., Bresci, E., Preti, F. & Penna, D. 2019 How does streamflow response vary with spatial scale? Analysis of controls in three nested Alpine catchments. *Journal of Hydrology* **570**, 705–718. https://doi. org/10.1016/j.jhydrol.2019.01.022.

Hashmi, M. Z. R., Masood, A., Mushtaq, H., Bukhari, S. A. A., Ahmad, B. & Tahir, A. A. 2019 Exploring climate change impacts during the first half of the 21st century on flow regime of the transboundary Kabul River in the Hindukush region. *Journal of Water and Climate Change* https://doi.org/ 10.2166/wcc.2019.094.

Hasson, S. 2016 Future water availability from Hindukush-Karakoram-Himalaya upper Indus Basin under conflicting climate change scenarios. *Climate* **4** (3). Available from: https://www.mdpi.com/2225-1154/4/3/40

Hayat, H., Tahir, A. A., Wajid, S., Abbassi, A. M., Zubair, F., Hashmi, Z. U. R., Khan, A., Khan, A. J. & Irshad, M. 2019 Simulation of the meltwater under RCP climate change scenarios in a poorly gauged snow and glacier-fed Chitral River catchment (Hindukush region). *Geocarto International* 1–15. https://doi.org/10.1080/10106049.2019.1700557.

He, X., Chaney, N. W., Schleiss, M. & Sheffield, J. 2016 Spatial downscaling of precipitation using adaptable random forests. *Water Resources Research* **52** (10), 8217–8237. https://doi. org/10.1002/2016WR019034.

Hoegh-Guldberg, O., Jacob, D., Taylor, M., Bindi, M., Brown, S., Camilloni, I., Diedhiou, A., Djalante, R., Ebi, K. L., Engelbrecht, F., Guiot, J., Hijioka, Y., Mehrotra, S., Payne, A., Seneviratne, S. I., Thomas, A., Warren, R. & Zhou, G. 2018 Impacts of 1.5°C global warming on natural and human systems. In: *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above pre-Industrial Levels and Related Global Greenhouse gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty* (V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E.

Lonnoy, T. Maycock, M. Tignor & T. Waterfield, eds).
In Press. Available from: https://www.ipcc.ch/sr15/chapter/
chapter-3/

Irmak, S., Irmak, A., Allen, R. G. & Jones, J. W. 2003 Solar and net
radiation-based equations to estimate reference
evapotranspiration in humid climates. *Journal of Irrigation
and Drainage Engineering* **129** (5), 336–347. Available from:
https://ascelibrary.org/doi/abs/10.1061/%28ASCE%
290733-9437%282003%29129%3A5%28336%29.

Jan, M., Jan, U. & Shah, G. M. 2014 Studies on fecundity and
gonadosomatic index of *Schizothorax plagiostomus*
(Cypriniformes: Cyprinidae). *Journal of Threatened Taxa* **6**
(1), 5375–5379. https://doi.org/10.11609/JoTT.o3269.5375-9.

Jiang, L., Ban, X., Wang, X. & Cai, X. 2014 Assessment of
hydrologic alterations caused by the Three Gorges Dam in
the middle and lower reaches of Yangtze River, China. *Water*
**6** (5), 1419–1434. https://doi.org/10.3390/w6051419.

Li, H., Sheffield, J. & Wood, E. F. 2010 Bias correction of monthly
precipitation and temperature fields from Intergovernmental
Panel on Climate Change AR4 models using equidistant
quantile matching. *Journal of Geophysical Research* **115**
(D10), D10101. https://doi.org/10.1029/2009JD012882.

Li, L., Shen, M., Hou, Y., Xu, C. Y., Lutz, A. F., Chen, J., Jain, S. K.,
Li, J. & Chen, H. 2019 Twenty-first-century glacio-
hydrological changes in the Himalayan headwater Beas river
basin. *Hydrology and Earth System Sciences* **23** (3),
1483–1503. https://doi.org/10.5194/hess-23-1483-2019.

Lutz, A. F., Immerzeel, W. W., Kraaijenbrink, P. D., Shrestha,
A. B. & Bierkens, M. F. 2016 Climate change impacts on
the upper Indus hydrology: sources, shifts and extremes.
*PLoS One* **11** (11). https://doi.org/10.1371/journal.pone.
0165630

Malmqvist, B. & Rundle, S. 2002 Threats to the running water
ecosystems of the world. *Environmental Conservation* **29** (2),
134–153. https://doi.org/10.1017/S0376892902000097.

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L.,
Harmel, R. D. & Veith, T. L. 2007 Model evaluation
guidelines for systematic quantification of accuracy in
watershed simulations. *ASABE* **50**, 885–900. Available from:
https://swat.tamu.edu/media/90109/moriasimodeleval.pdf.

Nafees, M., Rasul Jan, M. & Zahidullah, Z. 2012 Community
response to ban on fishing and associated environmental
problems: lesson learnt from River Swat, North of Pakistan.
*Interdisciplinary Environmental Review* **13** (2–3), 158–169.
https://dx.doi.org/10.1504/IER.2012.047795.

Naiman, R. J., Latterell, J. J., Pettit, N. E. & Olden, J. D. 2008 Flow
variability and the biophysical vitality of river systems.
*Comptes Rendus Geoscience* **340** (9–10), 629–643. https://
doi.org/10.1016/j.crte.2008.01.002.

Nash, J. E. & Sutcliffe, J. V. 1970 River flow forecasting through
conceptual models part I – a discussion of principles. *Journal
of Hydrology* **10** (3), 282–290. https://doi.org/10.1016/0022-
1694(70)90255-6.

Petts, G. E., Nestler, J. & Kennedy, R. 2006 Advancing science for
water resources management. *Hydrobiologia* **565**, 277–288.

Pfeiffer, M. & Ionita, M. 2017 Assessment of hydrologic alterations
in Elbe and Rhine Rivers, Germany. *Water* **9** (9), 684. https://
doi.org/10.3390/w9090684.

Poff, N. L. & Zimmerman, J. K. 2010 Ecological responses to
altered flow regimes: a literature review to inform the science
and management of environmental flows. *Freshwater Biology*
**55** (1), 194–205. https://onlinelibrary.wiley.com/doi/abs/10.
1111/j.1365-2427.2009.02272.x.

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L.,
Richter, B. D., Sparks, R. E. & Stromberg, J. C. 1997 The
natural flow regime. *BioScience* **47** (11), 769–784. Available
from: https://www.jstor.org/stable/1313099.

Poff, N. L., Olden, J. D., Merritt, D. M. & Pepin, D. M. 2007
Homogenization of regional river dynamics by dams and
global biodiversity implications. *Proceedings of the National
Academy of Sciences* **104** (14), 5732–5737. https://doi.org/10.
1073/pnas.0609812104.

Poff, N. L., Richter, B. D., Arthington, A. H., Bunn, S. E., Naiman,
R. J., Kendy, E., Acreman, M., Apse, C., Bledsoe, B. P.,
Freeman, M. C. & Henriksen, J. 2010 The ecological limits of
hydrologic alteration (ELOHA): a new framework for
developing regional environmental flow standards.
*Freshwater Biology* **55** (1), 147–170. Available from: https://
www.academia.edu/312750/The_Ecological_Limits_of_
Hydrologic_Alteration_ELOHA_a_New_Framework_for_
Developing_Regional_Environmental_Flow_Standards.

Qadri, M. Y., Mir, S. & Yousuf, A. R. 1982 *Journal of Indian
Institute of Science* **64**, 73–81.

Radchenko, I., Breuer, L., Forkutsa, I. & Frede, H. G. 2013, April
Runoff simulation in the Ferghana Valley (Central Asia)
using conceptual hydrological HBV-light model. In *EGU
General Assembly Conference Abstracts, 15.* Available from:
https://ui.adsabs.harvard.edu/abs/2013EGUGA.15.9249R/
abstract

Rafique, M. 2001 Fish fauna of the Himalayas in Pakistan with
comments on the origin and dispersal of its high Asian
elements. *Pakistan Journal of Zoology (Pakistan)* **33** (4),
279–288. Available from: http://agris.fao.org/agris-search/
search.do?recordID=PK2002000144.

Rafique, M. & Khan, N. U. H. 2012 Distribution and status of
significant freshwater fishes of Pakistan. *Records of the
Zoological Survey of India* **21**, 90–95. Available from: https://
www.semanticscholar.org/paper/Distribution-and-status-of-
significant-freshwater-Rafique/
01b01e7245f1275d054c04ee7d8b4145c952ee4d.

Richter, B. D., Baumgartner, J. V., Powell, J. & Braun, D. P. 1996
A method for assessing hydrologic alteration within
ecosystems. *Conservation Biology* **10** (4), 1163–1174.
Available from: https://onlinelibrary.wiley.com/doi/abs/10.
1046/j.1523-1739.1996.10041163.x.

Richter, B. D., Braun, D. P., Mendelson, M. A. & Master, L. L. 1997
Threats to imperiled freshwater fauna: amenazas a la fauna
dulceacuicola en riesgo. *Conservation Biology* **11** (5),
1081–1093. Available from: https://conbio.onlinelibrary.
wiley.com/doi/abs/10.1046/j.1523-1739.1997.96236.x.

Richter, B. D., Baumgartner, J. V., Braun, D. P. & Powell, J. 1998 A spatial assessment of hydrologic alteration within a river network. *Regulated Rivers: Research & Management: An International Journal Devoted to River Research and Management* **14** (4), 329–340. Available from: https://onlinelibrary.wiley.com/doi/10.1002/%28SICI%291099-1646%2819980708%2914%3A4%3C329%3A%3AAID-RRR505%3E3.0.CO%3B2-E.

Roy, A. H., Freeman, M. C., Freeman, B. J., Wenger, S. J., Ensign, W. E. & Meyer, J. L. 2006 Importance of riparian forests in urban catchments contingent on sediment and hydrologic regimes. *Environmental Management* **37** (4), 523–539. https://doi.org/10.1007/s00267-005-0029-1.

Seibert, J. 2000 Multi-criteria calibration of a conceptual runoff model using a genetic algorithm. *Hydrology Earth System Science* **4** (2), 215–224.

Seibert, J. 2001 On the need for benchmarks in hydrological modelling. *Hydrological Processes* **15** (6), 1063–1064. Available from: https://onlinelibrary.wiley.com/doi/abs/10.1002/hyp.446.

Seibert, J. 2005 *HBV Light Version 2.* User's manual. Stockholm University. Available from: https://www.geo.uzh.ch/dam/jcr:c8afa73c-ac90-478e-a8c7-929eed7b1b62/HBV_manual_2005.pdf

Seibert, J. & Vis, M. J. P. 2012 Teaching hydrological modeling with a user-friendly catchment-runoff model software package. *Hydrology and Earth System Sciences* **16**, 3315–3325. https://doi.org/10.5194/hess-16-3315-2012.

Serrat-Capdevila, A., Valdes, J. B., Perez, J. G., Baird, K., Mata, L. J. & Madock III, T. 2007 Modeling climate change impacts – and uncertainty – on the hydrology of a riparian system: the San Pedro Basin (Arizona/Sonora). *Journal of Hydrology* **347** (1–2), 48–66. Available from: https://www.sciencedirect.com/science/article/pii/S0022169407004799.

Shiau, J. T. & Wu, F. C. 2004 Assessment of hydrologic alterations caused by Chi-Chi diversion weir in Chou-Shui creek, Taiwan: opportunities for restoring natural flow conditions. *River Research and Applications* **20** (4), 401–412.

Shiau, J. T. & Wu, F. C. 2007 A dynamic corridor-searching algorithm to seek time-varying instream flow releases for optimal weir operation: comparing three indices of overall hydrologic alteration. *River Research and Applications* **23** (1), 35–53. Available from: https://onlinelibrary.wiley.com/doi/abs/10.1002/rra.962.

Shiau, J. T. & Wu, F. C. 2008 A histogram matching approach for assessment of flow regime alteration: application to environmental flow optimization. *River Research and Applications* **24** (7), 914–928. Available from: https://onlinelibrary.wiley.com/doi/10.1002/rra.1102.

Shrestha, S. & Nepal, S. 2019 Water balance assessment under different glacier coverage scenarios in the Hunza basin. *Water* **11** (6), 1124. https://doi.org/10.3390/w11061124.

Su, B., Huang, J., Gemmer, M., Jian, D., Tao, H., Jiang, T. & Zhao, C. 2016 Statistical downscaling of CMIP5 multi-model ensemble for projected changes of climate in the Indus River Basin. *Atmospheric Research* **178**, 138–149. https://doi.org/10.1016/j.atmosres.2016.03.023.

The Nature Conservancy 2009 *Indicators of Hydrologic Alteration Version 7.1 User's Manual.* The Nature Conservancy, Boulder, CO, USA. Available from: https://www.conservationgateway.org/Files/Pages/indicators-hydrologic-altaspx47.aspx

Usman, M., Ahmad, B. & Bukhari, S. A. A. 2019 Assessment of inter-seasonal, inter-annual and intra-annual variability in snow and rainfall recharged fresh water discharge under IPCC AR5 based climate change scenarios: a case study of Soan river basin, Potowar region, Pakistan. *Climate Change* **5** (20), 264–326. Available from: http://www.discoveryjournals.org/climate_change/current_issue/v5/n20/A6.pdf.

Van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J. F. & Masui, T. 2011 The representative concentration pathways: an overview. *Climatic Change* **109** (1–2), 5. https://doi.org/10.1007/s10584-011-0148-z.

Vu, T. T., Kiesel, J., Guse, B. & Fohrer, N. 2019 Analysis of the occurrence, robustness and characteristics of abrupt changes in streamflow time series under future climate change. *Climate Risk Management* **26**, 100198. https://doi.org/10.1016/j.crm.2019.100198.

Wijngaard, R. R., Lutz, A. F., Nepal, S., Khanal, S., Pradhananga, S., Shrestha, A. B. & Immerzeel, W. W. 2017 Future changes in hydro-climatic extremes in the Upper Indus, Ganges, and Brahmaputra River basins. *PLoS One* **12** (12). https://doi.org/10.1371/journal.pone.0190224

Willmot, C. 1982 Some comments on the evaluation of model performance. *Bulletin of the American Meteorological Society* **63** (11), 1309–1313. https://doi.org/10.1175/1520-0477(1982)063&lt;1309:SCOTEO > 2.0.CO;2.

Xue, L., Zhang, H., Yang, C., Zhang, L. & Sun, C. 2017 Quantitative assessment of hydrological alteration caused by irrigation projects in the Tarim River basin, China. *Scientific Reports* **7** (1), 1–13. Available from: https://www.nature.com/articles/s41598-017-04583-y.

Zolezzi, G., Bellin, A., Bruno, M. C., Maiolini, B. & Siviglia, A. 2009 Assessing hydrological alterations at multiple temporal scales: Adige River, Italy. *Water Resources Research* **45** (12). Available from: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2008WR007266