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Improved hydrological projections and reservoir management in the Upper Indus Basin under the changing climate

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Abstract

The availability of water resources plays an important role for the economy of a country. The nexus of energy-food-water are interlinked and of particular importance in the uncertain environment of developing countries. In Pakistan, agriculture contributes 25% to the gross domestic product. The Indus River contributes 44% of the available water to irrigation of crops and the ecosystem, and currently produces 5,112 MW electricity, with the potential to produce 38,602 MW electricity. This makes it important to investigate the status of water availability in the Upper Indus Basin under existing emission scenarios. In this study, the future availability of water is projected for the Indus River under the A2, B2, RCP4.5 and RCP8.5 emission scenarios. A meta-analysis has been conducted to present a combined picture by combining the results from the emission scenarios. Our meta-analysis shows higher confidence in RCPs projections. The results show that sufficient water will be available in the Indus River that will meet the demands of water in future but there will be scarcity of water in some months under each scenario. However, by proper management and optimum utilisation of the available water, this scarcity can be resolved.

Introduction

The scientific community around the globe combines efforts to cope with the worst impacts of the climate change on various key areas like water resources, energy, agriculture, health, drying up rivers, precipitation pattern and precipitation distribution, *etc*. (Global Trends 2025 2008; Urama & Ozor 2010). Climatic changes and their impacts are major concerns of Pakistan (National Climate Change Policy of Pakistan 2011). Water resources play a vital role in agriculture and energy sectors of this country. Agriculture contributes 25% of national gross domestic product of Pakistan (Piracha & Majeed 2011; World Bank 2014). In the energy sector, the hydropower contributes 36% of electricity production in the country [Water and Power Development Authority of Pakistan (WAPDA)]. In future, due to an increase in population, the demand of food and energy will also increase (Lal 2005; Food and Agriculture Organization – FAO 2011; World Economic Forum 2011). In Pakistan there are chains of rivers across the country, including Indus River that is one of the biggest rivers of the world. Previous data shows that Indus River contributes 44% of the total inflow annually, on a seasonal basis it contributes 86–88% of river flow in the Summer and 12–14% in the Winter season [Indus River System Authority (IRSA); Piracha & Majeed 2011; Khan & Pilz 2015].

Indus River has two reservoirs, including the world's largest earth filled dam, the Tarbela Dam (WAPDA). Tarbela dam produces 3,478 MW electricity and has the capacity to store 7,400.89 million m^3 water (WAPDA). It is a multi-purpose reservoir, in particular it serves the storage of water, hydropower generation and flood control. Therefore, the shortage of water in Tarbela reservoir will badly effect agricultural production and hydropower generation. Most of the research in climate change is now focusing on the impacts of climate change, water resources management under climate change and policy development to combat the impacts and retain an optimal level of sustainability (Arnell *et al*. 2011; Wiltshire *et al*. 2013; Olmstead 2014; Zhang & Balay 2014). Recently, many studies focus on water resources in the UIB and economy of Pakistan (Piracha & Majeed 2011; Cook *et al*. 2013). Cook at al. (2013) summarises the importance of UIB for Pakistan in a single sentence: 'Thus, as the Indus River Basin goes, so goes Pakistan'. In the HKH (Himalya-Karakorum-Hindukush) region, the inflow is very sensitive to temperature that causes glaciers and snow melting.

Table 1 Details about the climate model simulated meteorological data on maximum temperature, minimum temperature, and precipitation, based on different emission scenarios, observed hydrological and meteorological data utilized in this study

Simulated data			
RCMs	Scenarios	Baseline time period	Future time period
PRECIS	A2	1961–1990	2010–2039
PRECIS	B2	1961–1990	2010–2039
CCAM	RCP4.5	1975–2005	2006–2035
CCAM	RCP8.5	1975–2005	2006–2035
Observed data			
Meteorological data	____________	1961–1990	____________
Hydrological data	____________	1960–2005	____________

The RCMs used to derive the Global Climate Models (GCMs) and the corresponding scenarios are also mentioned.

Husain (2015) stated that the operation of the reservoir is probably more reliable if the impacts of a potential climate change are considered. Some studies found that climate change will alter the river flow differently in different seasons (Brekke *et al*. 2009; Matonse *et al*. 2013). Many studies reported that probably the optimal reservoir operation may be not optimal anymore due to the changing climatic conditions. The operational rules can be re-optimised by considering the changing hydro-meteorological conditions to increase the hydropower and limit flooding in the watershed (Minville *et al*. 2010; Eum *et al*. 2012; Alvarez *et al*. 2014).

In this study, we used four different emission scenarios of the Intergovernmental Panel on Climate Change (IPCC). The RCPs (representative concentration pathways) are the greenhouse gases emission scenarios which were considered as guidelines by IPCC for their fifth assessment report. The other two emission scenarios are the A2 and the B2 which were the guidelines of IPCC for their fourth assessment report AR4, 2007. Climate change projection from a single model may be uncertain due to several reasons, including, for example, structural and parametric uncertainties. Therefore, we need to produce combined projections using different models or scenarios by using meta-analysis or Bayesian Model Averaging (Min *et al*. 2007; Huang 2014; Dumont *et al*. 2015). A meta-analysis can be defined as the analysis of analysis or a systematic review of literature fully supported by statistical methods with the goal to combine the information from related studies (Glass 1976). It is a reliable method for combining the results from different experiments to produce more realistic results (Brooks 1997; Chen & Peace 2013).

The main goals of this paper are: to investigate the responses of water resources in Indus River under different emission scenarios in future and the response of Tarbela reservoir to the available water. Moreover, this study will also provide valuable information to assist policy makers and management in the area of agriculture, Tarbela Reservoir management, energy production and related areas in the future.

Analytical framework

The details of methodology, data sets and models are described in the following sub-sections. Data and models are discussed in section 'Data and Models', in Section 'River flow (I_t) projections', river flow projection is briefly discussed, Section 'Combined projections using meta-analysis' gives details about combined projections using meta-analysis which will help to understand which scenario is more reliable than others. Section 'Assessment of water availability and reservoir management' is reserved for assessment of water availability and reservoir management.

Data and models

The output of two regional climate models, PRECIS (Providing Regional Climate for Impact Studies) and CCAM (cubic conformal atmospheric model) is used with horizontal resolution of 50 by 50 km. This data was acquired from GCISC (Global Change Impact Studies Centre) and CORDEX (COordinated Regional climate Downscaling Experiments) for the South Asian region. The data of each scenario is divided into two chunks, baseline and future time period as given in Table 1. Daily data on maximum and minimum temperature, precipitation for five meteorological stations and daily river flow of Indus River upstream Tarbela Reservoir in the UIB are used in this study and graphically displayed in Fig. 1.

River flow (I_t) projections

To simulate historical and future river flows, the RCMs data (PRECIS with A2, B2 and CCAM with RCPs) is used as input to the hydrological model called University of British Columbia Watershed Model (UBCWM; Quick & Pipes 1972). The calibration and validation of UBCWM is performed for the periods of 1995–2004 and 1990–1994, respectively. The efficiencies of calibration and validation of UBCWM were calculated by using the coefficient of determination and the Nash-Sutcliffe coefficient (Nash & Sutcliffe 1970).

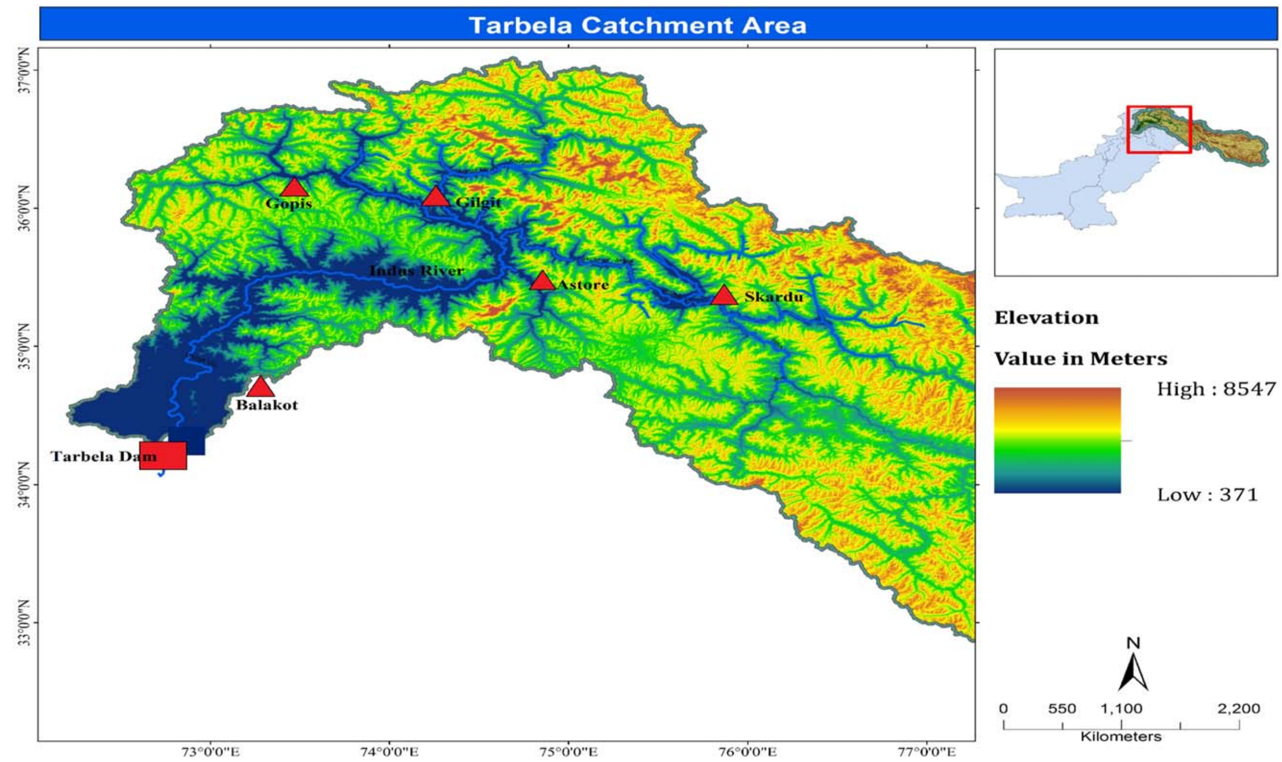

Fig. 1. Upper Indus Basin is shown in the small part of the figure on the right side while the area under study is enlarged. The locations of selected meteorological stations and Tarbela reservoir are indicated with triangles and a rectangle, respectively, with red color. [Colour figure can be viewed at wileyonlinelibrary.com]

Combined projections using meta-analysis

Meta-analysis is a statistical method which can be used to produce combined projections from individual model outputs. It gives weight to each study on the basis of its precision and consequently provides enhanced confidence in future projections. The three-step methodology is explained briefly in the following subsections.

Selection of the model

There are two basic models for meta-analysis: the fixed effect model (FEM) and the random effect model (REM) (Viechtbauer 2010). The FEM assumes that all the studies included in the meta-analysis come from a single homogeneous population or share a common effect (mean or average) while REMs assume that the effects of the studies included in the meta-analysis form a random sample from a population following a given distribution. The observed effects in the FEM and REM are mathematically given by Equations (1) and (2), respectively. Suppose we have k studies, and *let* θ denote the (true) intervention effect in the population which we would like to estimate. Further, let θ_k denote the k^{th} study effect and ζ_k the random effect in this study; $k=1, 2, \ldots, K$.

$$\theta_k=\theta+\varepsilon_k, \quad \varepsilon_k \sim N\left(0, \mathrm{v}_k{}^2\right) \tag{1}$$

$$\theta_k= \theta+\zeta_k+\varepsilon_k, \quad \zeta_k \sim N\left(0, \tau^2\right) \tag{2}$$

Here ϵ_k describes the variation within the k^{th} study and the random effects ζ_k reflect the variations between the considered studies.

FEM is a special case of REM when

$$\zeta_1=\zeta_2=\ldots=\zeta_K=0, \tag{3}$$

then the REM reduces to the FEM. Model selection is mainly based on the nature of the study (Borenstein *et al*. 2010; Chen & Peace 2013; Schwarzer 2015).

Weighting schemes for parameters estimation

Different weighting schemes are available for estimating the effect size in meta-analysis, the concrete choice depends on the nature of the study (Borenstein *et al*. 2010). We propose the so-called inverse-variance weighting technique for quantifying the effect size in our analysis. According to Borenstein *et al*. (2010), all the available schemes are efficient because they assign more weight to more precise studies. In case of a fixed-effect model the weights are calculated by Equation (4).

$$\omega_k = \frac{1}{v_k{}^2} \tag{4}$$

where $\boldsymbol{\omega_k}$ and $\boldsymbol{v_k}$ are the weight and variance, respectively, of k^{th} study.

In the REM the weights are calculated by Equation (5).

$$\omega_k{}^* = \frac{1}{v_k{}^*},\ v_k{}^* = v_k{}^2 + \tau^2 \tag{5}$$

$\omega_k{}^*$ is the weight for the k^{th} study and $v_k{}^*$ is the combined variance of within-study $\left(v_k{}^2\right)$ and between-studies (τ^2). The weights for estimating the effect size depend on the model chosen in the model specification stage.

Estimation of parameters

The next step is to estimate the unknown parameters of the specified model by incorporating the weighted least squares method given by Equation (6).

$$\theta_c = \frac{\sum_{k=1}^{K} W_k.\theta_k}{\sum_{k=1}^{K} W_k}$$

$$W_k = \frac{1}{var(\theta_k)} \tag{6}$$

The $(1-\alpha)$% confidence interval of the combined estimator is given by

$$\theta_c \pm Z_{\left(1-\frac{\alpha}{2}\right)} \times SE(\theta_c)$$

where θ_c is the combined size effect given above and $SE(\theta_c)$ is the associated standard error, $Z_{\left(1-\frac{\alpha}{2}\right)}$ is the $\left(1-\frac{\alpha}{2}\right)$-quantile of the standard normal distribution.

Assessment of water availability and reservoir management

The availability of water and the operation of Tarbela Reservoir under different emission scenarios are important and have implications in various areas vulnerable to climate change. The important parameters used while investigating the availability of water and reservoir management in the Indus River include Maximum operating storage, dead level storage, area of the reservoir, maximum discharge capacity by using outlet works and spillways. The availability of water in Tarbela Reservoir is modelled according to Equation (7) which will provide useful information about the status of the reservoir, the number of times to open spillways and water availability in future.

In order to investigate water availability and reservoir management under different emission scenarios, we used Equation (7) with the help of which extra outflow (O_{ext}: more than maximum operating storage) is calculated.

$$\boldsymbol{S_{t+1}} = S_t + I_t - O_t - \boldsymbol{E_t}.\mathbf{A} \tag{7}$$

$$\boldsymbol{Oext_{t+1}} = \begin{cases} =0 \ \ if\ \ \boldsymbol{S_{t+1}} \le 7400.89\ \ Million\ \ \boldsymbol{m}^3 \\ >0\ \ if\ \ \boldsymbol{S_{t+1}} > 7400.89\ \ Million\ \ \boldsymbol{m}^3 \end{cases}$$

where S_t is maximum operating storage, $\boldsymbol{I_t}$ is simulated river flow, $\boldsymbol{O_t}$ is outflow, $\boldsymbol{E_t}$ is evaporation in mm at time $\boldsymbol{t}$, A is the area of the reservoir, $\boldsymbol{Oext_{t+1}}$ is extra outflow at time $\boldsymbol{t}+1$, which should be spilled out. The subscript t in Equation (7) represents frequency of the data (monthly in this study). To accomplish the analysis four stochastic terms on the right side in Equation (7) need to be calculated, this will be done in the following subsections:

Evaporation (E_t)

Evaporation in Equation (7) is calculated by Equation (8) from Blaney & Criddle (1950).

$$E_t = k.p.(0.46.T_m + 8.13) \tag{8}$$

Here, T_m is the mean monthly temperature in °C, p is the percentage of the total daytime hours for the period used out of the total daytime hours of the year, k is the monthly consumptive coefficient depending on the vegetation, topography, land-use and season of the study area.

Calculating outflow (O_t) using Bayesian Dynamic Linear Modelling

Tarbela Reservoir has four tunnels and two spillways. The maximum discharge capacity of tunnels is 32,304.90 million m^3month^{-1} and that of spillways is 110,100.59 million m^3month^{-1}. The calibrated Bayesian dynamic linear model (BDLM) using historical observed outflow for the duration of thirty years is used to forecast the outflow for the future time period. DLM's are popular tools for modeling and forecasting because they do not require stationarity and can handle time series with sudden jumps and structural breaks in an elegant way. Let O_t denote the outflow observation at time $t=1,2,\ldots,n$, then the observation and state equations for the outflow time series are represented by Equations (9) and (10), respectively.

$$O_t = F_t.\theta_t + d_t,\ \ d_t \ \sim\ N(0,V) \tag{9}$$

$$\theta_t = G_t.\theta_{t-1} + \omega_t,\ \ \omega_t \ \sim\ N(0,W) \tag{10}$$

where $\boldsymbol{\theta_t}$ is a vector of unobserved states of the system of length $\boldsymbol{m}$ that are assumed to evolve over time according to the linear system operator $\boldsymbol{G_t}$ (state transition), a matrix of

$$\begin{array}{ccccccccccccc} \theta_0 & \rightarrow & \theta_1 & \rightarrow & \theta_2 & \rightarrow & \cdots & \rightarrow & \theta_{t-1} & \rightarrow & \theta_t & \rightarrow & \theta_{t+1} \rightarrow \cdots \\ & & \downarrow & & \downarrow & & \cdots & & \downarrow & & \downarrow & & \downarrow \cdots \\ & & O_1 & & O_2 & & & & O_{t-1} & & O_t & & O_{t+1} \end{array}$$

Fig. 2. Dependence structure of a state-space model.

order ($\boldsymbol{m}\times\boldsymbol{m}$). Then the observations can be expressed as in Equation (9). We observe a linear combination of the states with a matrix $\mathbf{F_t}$ ($\mathbf{m}\times\mathbf{p}$), which serves as observation operator that transforms the model states to a time series observation. The idea behind the state-space or DLM models is that the time series ($\boldsymbol{O_t}$ in our study) can be modelled as an incomplete and noisy function of some unobservable process $\boldsymbol{\theta_t}$, $\boldsymbol{t}=1, 2, \ldots, \boldsymbol{n}$, called the state evolution process. To predict the next observation ($\boldsymbol{O_{t+1}}$) given the previous observations ($\boldsymbol{O}_1, \ldots, \boldsymbol{O_t}$) it is important to describe the probability law of the process ($\boldsymbol{O_t}$). The dependence structure of the outflow observation is given in Fig. 2.

Both equations, the observation equation and the state equation have Gaussian errors distributed with means zero and covariance matrices V and W, respectively. It is assumed that the initial state θ_0 follows a Gaussian distribution

$$\theta_0 \sim N(m_0, C_0)$$

with fixed (non-random) vector m_o and (non-random) matrix C_0. For further details we refer to Pole *et al*. 1994.

Results and discussion

The results about climate change and their implications on water resources, hydrological projections and management of Tarbela Reservoir under the projected hydrological responses are detailed in the following sub-sections.

Climate and hydrological changes

Climate data is used to assess climate change and after the application of statistical bias correction techniques it is further used as input data to UBCWM to simulate river flow in the Indus River for the baseline periods and future periods under different scenarios. From Table 2 we can see that maximum temperature, minimum temperature and precipitation are changing in all considered scenarios in future time period as compared to the baseline period. The average change in maximum temperature is 1.54°C, for minimum temperature it is 1.23°C while the average change in precipitation is 15.22%. The largest average change in maximum temperature is observed under the RCP4.5 and the smallest average change is observed under the B2 scenario. The largest average change in minimum temperature is noted under the A2 scenario and the smallest average change in minimum temperature is noted under the RCP4.5. With regard to precipitation, maximum average change is observed under the A2 projections while minimum average change is observed under the B2 projections.

During the calibration of UBCWM we got $R^2=0.89$ and Nash-Sutcliffe $=0.87$, whereas during validation the efficiency measurement statistics got improved values of $R^2=0.90$ and Nash-Sutcliffe $=0.89$. We made much more experiments to further improve the efficiency statistics but did not observe any improvements and thus decided to use the UBCWM with efficiencies given above. The results of river flow projections and changes in river flow show that river flow has increasing trend in future with respect to the

Table 2 Summaries of the projected climatology of the Upper Indus Basin including projected maximum temperature, minimum temperature, and precipitation under different climate change scenarios

	Maximum temperature			Minimum temperature		
Scenarios	Baseline period	Future period	Change	Baseline period	Future period	Change
Observed	21.50 ± 0.49			8.59 ± 0.08		
A2	21.66 ± 0.49	23.16 ± 0.51	1.50 ± 0.21	9.10 ± 0.45	10.75 ± 0.48	1.65 ± 0.29
B2	21.76 ± 0.48	22.87 ± 0.50	1.11 ± 0.22	9.14 ± 0.44	10.56 ± 0.53	1.42 ± 0.31
RCP4.5	23.82 ± 0.52	22.78 ± 0.54	1.96 ± 0.22	9.95 ± 0.46	10.81 ± 0.48	0.85 ± 0.35
RCP8.5	23.82 ± 0.51	25.40 ± 0.53	1.58 ± 0.21	9.95 ± 0.46	10.94 ± 0.44	0.99 ± 0.26
Average projections	22.77 ± 0.50	24.30 ± 0.52	1.54 ± 0.215	9.54 ± 0.45	10.77 ± 0.48	1.23 ± 0.31
	Precipitation			River flow		
Observed	2.03 ± 0.25					
A2	2.04 ± 0.24	2.70 ± 0.37	32.35 ± 0.27	2368 ± 151	3,975 ± 244	33.01 ± 8.15
B2	3.66 ± 0.19	3.86 ± 0.18	5.46 ± 1.84	3341 ± 192	4,180 ± 241	2358 ± 6.75
RCP4.5	3.29 ± 0.35	3.68 ± 0.47	11.85 ± 1.89	2769 ± 144	3,701 ± 189	43.18 ± 7.51
RCP8.5	3.29 ± 0.10	3.66 ± 0.14	11.24 ± 0.78	2769 ± 136	3,729 ± 178	40.70 ± 4.80
Average projections	3.07 ± 0.22	3.48 ± 0.29	15.22 ± 1.20	2811 ± 156	3,896 ± 213	34.97 ± 5.44

A short summary about water availability and changes in river flow is also presented. The table further presents changes in projected variables. The values of temperature are shown in °C, for precipitation in mm day^{-1}, while in m^3 s^{-1} for river flow. Each value refers to the average value of a variable with the corresponding margin of error (some researchers called it sigma limits). Average projections are calculated on the basis of simulated data sets.

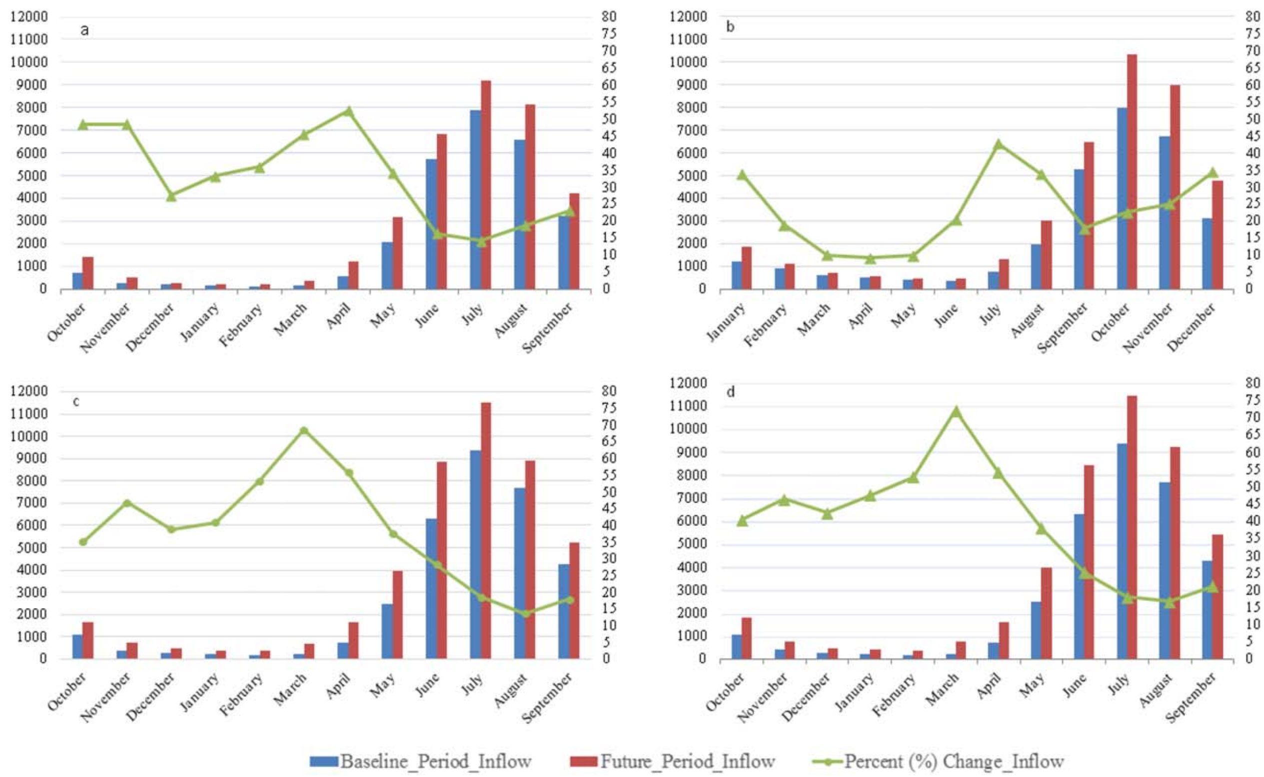

Fig. 3. This figure shows river flow and percent changes in river flow under different emission scenarios in Indus River. The top left graph shows the results under the (a) A2 scenarios, (b) under the B2 scenarios, (c) under the RCP4.5 and (d) under the RCP8.5. The comparison between base line and future river flow is on the primary axis while the percent change in river flow is presented on the secondary axis. The units of measurement on both axes are cubic meter per second (m^3s^{-1}). [Colour figure can be viewed at wileyonlinelibrary.com]

baseline period for each projected scenario. The river flow calculated for the baseline period, projected river flow for future and percent (%) changes in river flow are given in Fig. 3. The results show that the percent increase is higher during Winter as compared to the percent increase during the Summer season. From Fig. 3 it can be easily inferred that there is almost 40–45% increase in river flow in Winter while there is almost 20–25% increase in river flow during Summer in all considered scenarios except the B2 scenario which behaves slightly different. Under the B2 scenario, during Winter season the increase in river flow is 10–15% while during the Summer season the river flow is increasing by 22–30%.

A meta-analysis was conducted to present a combined picture of hydrological projections by combining the results from considered scenarios. Meta-analysis gave higher weights to RCPs projections under both REM and FEM and thus shows higher confidence in the said scenarios as compared to the A2 and B2 scenarios. The highest and lowest weights are assigned to the RCP85 and B2 scenarios, respectively, given in Fig. 4. It can be seen from Fig. 4 that the absolute mean difference between the baseline period and the future period is higher in the A2 scenario while it is minimum in the B2 scenario. The 95% confidence interval shows that the RCP85 has higher precision while the A2 scenario has lower precision. The combined differences are almost similar in REM and FEM but the 95% confidence interval is wider for the REM, because this model considers the variation within studies as well as between studies.

Assessment of water availability and reservoir management

To assess water availability, Tarbela Reservoir is used as a measurement tool to investigate the availability of water in Indus River for the future time period with respect to the baseline period. In Equation (7), we calculate storage for the next time (future) on the basis of present storage of the reservoir, simulated river flow, forecasted outflow and evaporation from the reservoir. The river flow is simulated by using the UBCWM, outflow is calculated by using BDLM and Evaporation is calculated by using the formula of Blaney & Criddle (1950). The comparison of observed outflow and predicted outflow using the BDLM and the model diagnostic results are given in Figs. 5 and 6, respectively. Maximum operating storage of the Tarbela Dam is approximately 7,400.89 million m^3 and the dead level storage of the Dam is 2,392.96 million m^3. Thus, when the storage is less than the dead level storage,

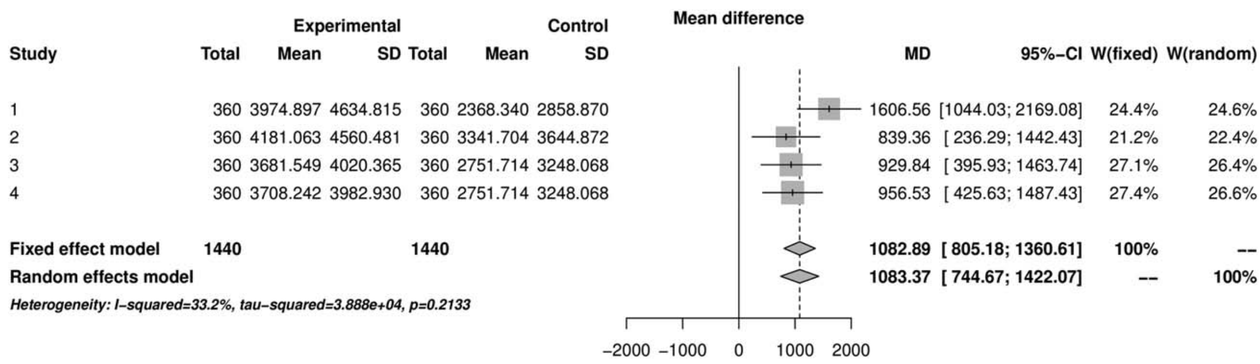

Fig. 4. Forest plot of the meta-analysis for the hydrological projections under four different climate change scenarios. The figure shows the individual results for each scenario and a combined weighted result for the river flow with their corresponding 95% intervals. Study numbers stand for the following scenarios: (1) A2 scenario, (2) B2 scenario, (3) RCP4.5 and (4) RCP8.5. In the figure control and experimental mean baseline and future duration of the study are shown. The unit of river flow is m^3s^{-1}. The calculations were done using the R-packages 'meta' and 'metafor'.

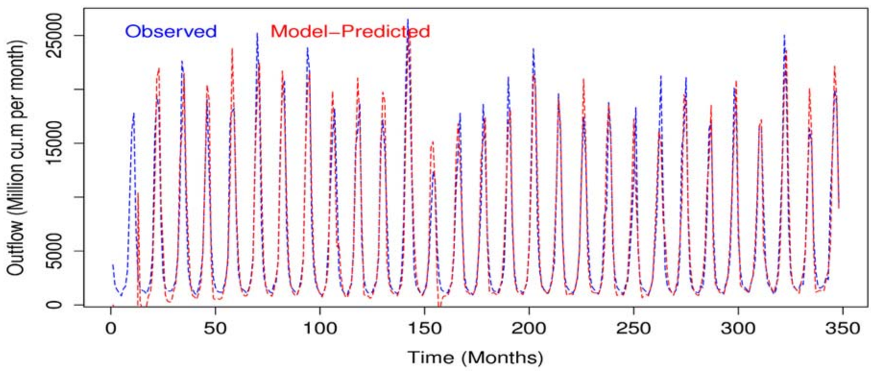

Fig. 5. Observed outflow (blue color) and predicted counterpart using a Bayesian dynamic linear model (red color) from Tarbela Reservoir. The unit of outflow is million m^3month^{-1}. The calculations were done using the R-package 'dlm'. [Colour figure can be viewed at wileyonlinelibrary.com]

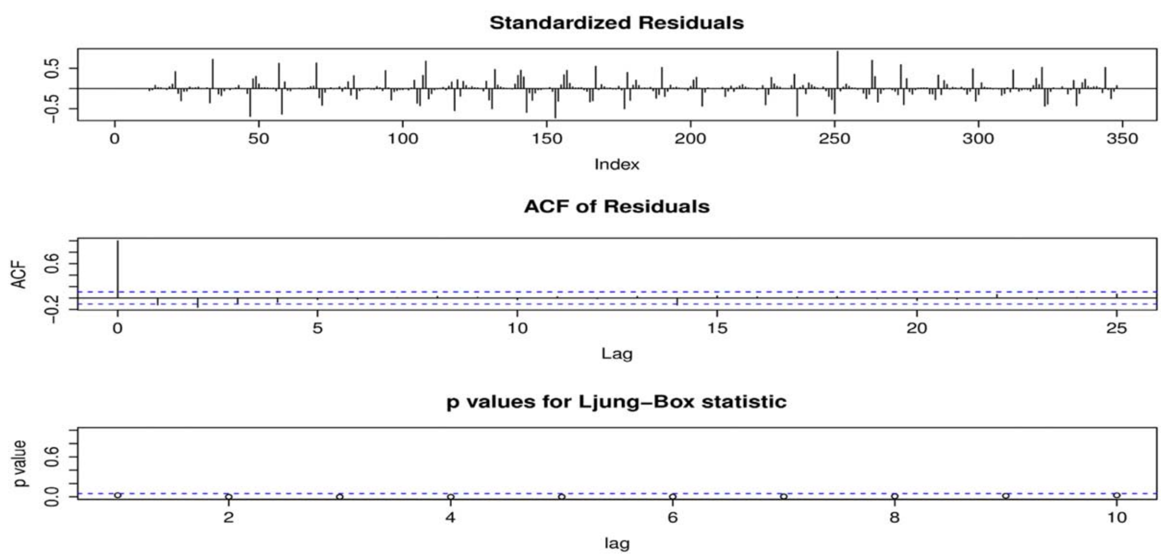

Fig. 6. Details about the residuals of the fitted Bayesian dynamic linear model to outflow series, standardised residuals, ACF and *P*-values for the Ljung-Box statistic are presented. The calculations were done using the R-package 'dlm'. [Colour figure can be viewed at wileyonlinelibrary.com]

Table 3 Statistics under the different climate change emission scenarios using simulated river flow, forecasted outflow, maximum operating storage and evaporation, and using important parameters of the Reservoir at Tarbela, UIB, Pakistan

Statistics show how many times the particular threshold is crossed under each climate change emission scenario using simulation results of UBCWM at Tarbela Reservoir, UIB, Pakistan

	Parameters	Dead level storage	Maximum operating storage	Total discharge by tunnels	Total discharge by spillways and tunnels	Between dead level storage and maximum operating storage
Scenarios	Duration	Original values 2,392.96 million m^3	7,400.89 million m^3	32,304.90 million m^3	142,405.48 million m^3	
A2	1961–1990	27	185	14	0	134
	2010–2039	13	209	38	0	100
B2	1961–1990	16	254	10	0	90
	2010–2039	10	265	39	0	85
RCP4.5	1976–2005	58	103	1	0	199
	2006–2035	19	205	19	0	136
RCP8.5	1976–2005	58	103	1	0	199
	2006–2035	16	2017	14	0	130

Four scenarios are considered in this analysis, the A2, B2, RCP4.5, and RCP8.5 scenarios of the IPCC.

we say that there is shortage of water and when it crosses the maximum operating storage we say that there is more water available. It can be analyzed whether more water will be available in future by comparing the statistics in Table 3 for the baseline period and future time period. The total discharge capacity by outlet works is 32,304.90 million m^3 month^{-1} while the total discharge capacity by two spillways is 110,100.59 million m^3 month^{-1}.

Table 3 presents monthly output results of the availability of water in Indus River, which show that the water level in Indus River has increasing trend in future under each scenario. We have a total of three hundred and sixty (360) months for thirty (30) years each for the baseline period and future time period. Besides the increase in water availability there are some months which have water scarcity under each scenario in future but the number of those months will be smaller in future time periods as compared to the baseline periods. The results show that the water surface in the reservoir will cross the maximum operating storage 209, 265, 205 and 217 times out of 360 times during the future time periods under the A2, B2, RCP4.5 and RCP8.5 scenarios, respectively. In other words, there will be more water available that can be released by outlet works or spilled out by spillways if it crosses the maximum discharge capacity of the outlet works. The total discharge capacity by tunnels is 32,304.90 million m^3 month^{-1} which will be crossed 38, 39, 19 and 14 times in future under the A2, B2, RCP4.5 and RCP8.5 scenarios, respectively, after keeping the maximum storage of the reservoir. This means that for the abovementioned times it will be probably necessary to open spillways to spill out extra water. The total discharge capacity of the reservoir (tunnels + spillways) is 142,405.48 million m^3 month^{-1}. The results show that this threshold will not be crossed during the entire period, whichever of the scenarios we postulate.

From Table 3 it can be seen that the number of hitting times of the dead level storage of the reservoir is decreasing in future. Similarly, the number of crossings of the maximum operating storage of the reservoir and the number of times the outflow of the reservoir crosses the maximum discharge capacity of the outlet works (tunnels) are increasing over time as compared to the baseline period. The other important parameter is the number of times the water level will remain between the maximum operating storage and dead level storage, which is decreasing in future. So, all these parameters show that there will be more water available in the Indus River in the future. The results have important implications particularly in the areas of agriculture, hydropower generation and the management of the Tarbela Reservoir. Our suggestions to the concerned stakeholders would be: Construct more reservoirs and install more storage capacities to overcome the problem of shortage of water and to store water during the high inflow in order to utilize it during the times of shortage of water. This may also increase the hydropower generation capacities which will then assist the national grid by contributing cheap and clean electricity. Raising the public awareness about optimal utilization of available water can also reduce the effects of water scarcity. The construction of more reservoirs and storage capacities will make the groundwater level rise or at least keep at the current level because the groundwater level is correlated with water levels in reservoirs (Seeboonruang 2012).

Conclusion and recommendations

The projected climate is changing over the study area under all considered scenarios. The average change in maximum temperature is 1.54°C and the average change in minimum temperature is 1.23°C. Precipitation changes on the average by 15.22% under the considered scenarios. Comparisons between the availability of water during the baseline period and future time period show that there will be enough water available in the future but UIB has water scarcity in only few months under each scenario. The overall situation of the availability of water becomes better in the future compared to the baseline period. Almost all indicators show increase in the amount of water in future. The frequency of crossings of the maximum discharge capacity of outlet works (tunnels) is increasing as well. It can be concluded from these statistics that there will be more water available in the future as compared to the baseline periods. The results show that there is no chance of overtopping of the reservoir in the future. Meta-analysis shows higher confidence in RCPs projections which are the latest guide lines for the fifth assessment report of IPCC. The A2 scenario provides least confidence while RCP8.5 offers more confidence in future projections. The combined mean difference is almost similar in both FEM and REM but the precision of the former is higher than that of the latter. Similar results had been reported in previous studies (Ress & Collins 2006; IPCC 2007a, b; Immerzeel *et al*. 2013; Ali *et al*. 2015; Khan *et al*. 2015), stating that those parts of the globe which are relatively dry are likely to face further water scarcity while other parts like South Asia and some parts of Europe will probably have more water. Most probably the reasons of increase in water availability is high altitude, where a rise in temperature is more likely than in plain areas (IPCC 2007a, b), this will expedite the glaciers and snow melting process.

UIB is one of those basins where river flow has major contributions from glacier and snow melt and precipitation. The quantification of these contributions could be an important topic for future research. The research results could assist the flood forecasting division, and other concerned parties to cope with the flood situations which are happening continuously since the mega flood of 2010. Once we get clear results about this issue we can establish an Early Warning System for flood occurrence in future that will help to reduce the risk of casualties and losses. Construction of more dams and water storage capacities could minimise the water scarcity issue, improve flood control and assist in the solution of the energy crisis of the country lasting for some years now.

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